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U.S. NAVAL AVIONICS FACILITY

INDIANAPOLIS, INDIANA

TECHNICAL REPORT

DIRECTOR OF RESEARCH AND ENGINEERING

Report Number TR-7 25 October 1960

MICROELECTRONICS
A STATE-OF-THE-ART REPORT (U)

(TED Project AVFI-AV-44007)

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U.S. NAVAL AVIONICS FACILITY

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TECHNICAL REPORT

DIRECTOR OF RESEARCH AND ENGINEERING

(14) NAFI-

Report Number TR-7 (11) 26 Oct[redacted]60

MICROELECTRONICS.

STATE-OF-THE-ART REPORT. (U)

(16) TED [redacted] AVFI-AV-44007

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PREFACE

No attempt is made in this report to completely cover the field of microminiaturization of electronic equipment. Rather, this represents the authors' summary and evaluation of what they believe to be the more promising and realistic approaches to microcircuitry. Also, included is a report of the accomplishments made at this facility. Finally, along with a note of caution, some speculations on the future are presented.

There are a number of excellent reports available, some of which are listed in the bibliography.

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1. CONCLUSIONS

The state-of-the-art is in such a turmoil that it is impossible, at this time, to predict the ultimate form it will assume. No one concept should be generally accepted at this time - at least by the military. In the interest of industrial preparedness, all concepts should be carefully followed and understood by responsible military representatives. Great strides are being taken forward and more are inevitable as scientists learn more about physics of the solid state.

For purposes of discussion and reference in this report, micro-electronics concepts have been arbitrarily classified as follows:

(1) Packaging.

(2) Integrated Circuit (ceramic substrate).

(3) Integrated Circuit (semiconductor substrate).

(4) Functional Blocks.

The microcard concept is a reality now and is gaining acceptance. A list of microcomponent suppliers appears in Appendix A. There is considerable optimism about the others.

II. RECOMMENDATIONS

It is strongly recommended that this program receive unqualified support not only at this facility but at other Naval establishments as well. All these efforts should be coordinated so as to avoid as much duplication as possible and to realize the greatest return for the investment. The survey reported here revealed the state-of-the-art is in such a transitional state that this appears to be an opportune time for the Navy to provide direct support and supervision of its own research and development programs on microelectronics.

In consideration of this, the following recommendations or suggestions are presented for serious consideration:

a. That an intra-Navy panel or working group composed of individuals who have technical backgrounds be established. This group should keep abreast of the latest innovations so as to be able to evaluate the Navy's current and projected requirements. It should assume technical leadership at all times and guide, encourage, or in some cases discourage, certain selected efforts.

b. Presently available knowledge, techniques and devices should be used now, where applicable, for prototype equipment under consideration. Two concepts seem to be feasible at this time, namely, modules with thin film evaporated passive components containing inserted active components, and microcards wherein all components are inserted. The purpose in applying these techniques now is to gain practical experience in their application and to gather operational data for reliability studies.

c. That a 10-year program be initiated; the objective of which shall be to study development and application of solid state devices capable of performing complete logic functions within their crystallographic domains per se.

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III. BACKGROUND AND HISTORY OF THE PROBLEM

Since the introduction of the transistor in 1948, more funds and effort have been expended on miniature electronic systems than was spent developing the atomic bomb. From the present plateau, the future of electronics appears limitless.

At least 200 government and commercial interests in this country and abroad are known to be actively engaged in some phase of microelectronics and its applications.

In spite of its fabulous potentialities, it is wise to keep one's feet on the ground. As in any enterprise it takes time to become seasoned and mature. Molecular and solid state functional systems offer great promise as a means of achieving miniaturization so vital to the military establishment. However, much more research and development is required. Most of the units currently available are relatively simple and designed to handle little power. There is reason to believe future models will handle several watts and more. Witness the following which appeared in a report from Radiochemistry Branch of AFCRC:

"Improvements in existing electronic equipment, using available materials, have for the most been pushed nearly to their limits. If greater reliability of function, new and desirability functions and major break-throughs are to be realized, they must for the most part come from new and improved materials."

Also the following:

"This is the age of rapid change - in which "going into production" means obsolescence. With the bitter lessons of the transition from aircraft to missiles so fresh in their memories, many companies will appreciate this fact, will recognize the need for thinking ahead.

"There are those, however, who - happy and complacent in the wonders of their own accomplishments - will some day discover that once again the military airplane business seems to be dying out." (Seabrook Hull, SPACE, Missile Design & Development, January 1960).

The NAFI laboratory has no intention of "forsaking all others" in pursuing any one microminiature concept. Applied research personnel at this station have had more than 50 years combined experience in vacuum technology and thin-film fabrication. The leader of this group produced some of the first thin-film components 15 years ago and has maintained an active continuous interest in the field. This laboratory is equipped and staffed to perform and evaluate most any thin-film technique.

For the past year and a half, personnel in this laboratory have been making an extensive survey of the state-of-the-art. This is a three-prong attack:

1. Literature survey

2. Personal contacts with more than 40 industrial and commercial leaders in the field

3. Fabricating thin-film circuits for experience, test and evaluation.

As an agency of the Department of Defense and especially of the Industrial Preparedness Program, this laboratory has been "courting all suitors". In addition to maintaining a weather-eye for all new and novel approaches, this laboratory has made a few original contributions of its own.

IV. APPROACHES TO MICROELECTRONICS

After more than a decade or so of attempting to reduce the size and weight of electronic equipment by several different approaches, four appear to be emerging as leaders. As of this writing the field appears to be narrowing to four approaches which may be prophetic of into what form electronic equipment will ultimately crystallize.

It is anticipated that greater reliability, plus improved materials and reduction of costs will accompany reduction in size and weight.

1. Packaging Techniques

This refers primarily to various and novel means of packaging conventional miniature components as well as other discrete ones of special geometrical shape.

2. Integrated Circuitry on Ceramic Substrate

Integrated circuitry is intended to include that group in which a number of active and passive components are attached or fabricated in situ by one or more of a combination of several thin film deposition techniques on to a glass or ceramic substrate.

3. Integrated Circuitry on Semiconductor Substrate

In this concept complete operational circuits are formed in place on semiconducting substrates. By using various alloying, diffusion and evaporation processes, both active and passive components are formed on a single wafer.

4. Functional Blocks

Here individual components cease to exist. Rather a block of a specially grown and doped crystal performs a complete circuit function.

Components for High Temperature Ambients

In the forseeable future many components and assemblies will be required to operate in higher temperature environments. Two approaches are being seriously considered by various researchers. First, using components available now, cooling by electrical or mechanical means and, second, develop new materials able to perform the necessary circuit functions in the presence of high ambient temperatures. A considerable amount of material has been published about the mechanical cooling of equipment, but most observers feel it will require excessive power and penalize the primary power plant too much.

Several materials are available for high temperature passive

component application, but relatively few for active components. A few are some of the carbides, silicides and phosphides. Basic materials studies are being pursued by several laboratories under contract to government agencies. The search for new materials able to operate in high ambient temperatures must be diligently pursued, because as the terminal velocity of vehicles is increased the effective stagnation temperatures increase logarithmically.

<u>Manufacturing Economy</u>

"Several factors can run the cost of manufacturing microminiature equipment unreasonably high.

1. Expensive capital equipment may be required for automatic assembly or processing.

2. Design changes may run up the manufacturing cost by obsoleting intricate special tooling.

3. Low yield may result if tight process controls are required, particularly if a defect in any one of several sequencial operations can result in the rejection of a considerable portion of an equipment.

4. Inflexibility of the packaging system can adversely affect parts costs and availability, particularly where there are severe dimensional constraints on parts. Such packaging systems can be obsoleted by newer developments." (Ramo-Wooldridge Proposal)

A. THIN FILM MICROCIRCUITRY

The thin-film approach to microelectronics is a quasi two-dimensional concept for the fabrication of electronic circuitry on a thin flat wafer substrate. The present state-of-the-art limits the application of this approach to the deposition of thin film conductors, insulators and resistors to form passive resistive, inductive, and capacitive (RLC) networks. The network may be rendered active by soldering or otherwise attaching transistors and diodes in the circuit.

Thin-film microcircuitry in its present state of development is similar to conventional circuitry. In general, individual components retain their respective identities and conventional circuit design techniques are usually applicable. There are two notable exceptions: high-value components cannot be formed but distributed parameter RC networks can be produced by thin-film techniques.

Although thin-film circuitry occupies near zero volume, it requires appreciable area because the value of a deposited component is a function of its area. Because of area limitations only relatively low-value resistors, inductors, and capacitors are available to the circuit designer. As of now, the limits are approximately 100,000 ohms for resistors, 10 microhenries for inductors, and one microfarad for capacitors. Even these values are difficult to attain on microcircuit substrate wafers (less than 1 inch square).

Eventually, the development of new materials and techniques may raise these limits.

Since lumped parameters exist in thin-film microcircuitry and conventional printed circuitry, it would appear that their design procedures would be identical. However, there are important differences. In order to provide continuity of circuitry from one side of a board to the other, relatively few design problems are encountered in laying out a conventional printed circuit board, because eyelets or plated through holes may be conveniently located. In thin-film microcircuitry, holes, if there must be any, must be located from one side so as not to interfere with thin-film components on the other side. The most reliable means for providing electrical continuity between faces of the substrate wafer is through transistors or diodes mounted in holes in the wafer. This constraining feature introduces several design problems.

The designer of printed circuitry has only to specify circuit component values, tolerances, and wattage ratings, and usually is not severely restricted as to the dimensions of the circuit board. On the other hand, the designer of thin-film microcircuitry is confronted with more complex problems. First of all, the dimensions of the substrate wafer may be fixed; and, as a rule, the wafer area is one-half square inch or less. The size of the wafer not only restricts the amount of circuitry that can be deposited, but also limits the values of the deposited components.

In order to take maximum advantage of the available area, it is desirable to make the layout as compact as possible. The minimum space between components is governed by several factors such as operating voltages, frequencies and the resolution of the masking devices that define the areas of deposited materials.

If the circuitry is divided between both sides of a wafer, as many as eight masks are required. (See Figure 1.) If all the circuitry is deposited on one side of a wafer, 18 masks are needed in a process for depositing a relatively simple circuit. (See Figure 2.)[27]

At present the thin-film concept suffers from a low yield in manufacturing. Consider, for example, the above-mentioned circuits requiring 8 (or 18) masks for their production. Each mask defines the deposition for one or more circuit elements on each wafer during an evaporation cycle. Hence, circuit yield is the product of the average yield for each evaporation cycle. If the average yield per cycle is 90% (a very high yield), the circuit yield would be 0.90^8 or 43% (similarly, for a circuit requiring 18 masks for its fabrication, the yield would be only 15%). These figures are disconcerting, to say the least. However, the economic outlook for thin-film microcircuitry may not be as gloomy as it appears at first glance. Regardless of the method of deposition used for producing thin-film circuits, the costs of the deposited materials are negligible. If glass is used as substrates, a relatively low yield of acceptable circuits is not serious. However, production economics become more severe when more expensive materials are used as substrates. Labor and equipment time are also factors that must be considered for the economic production of micro-

circuitry.

The fabrication processes described above are "additive" in that individual layers are deposited in specific geometric patterns. Haloid Xerox uses a "subtractive" method for fabricating similar circuitry. They describe the subtractive process as follows:

"Except for the dielectric film, each layer is deposited on the substrate without benefit of masking. Each successive evaporation, therefore, completely covers the preceding layer. (See Figure 3A.) The geometry of the individual layers is determined by selective etching, after the plates are removed from the vacuum chamber. . . To convert the circuit plate to a functional RC circuit, a series of stencilling and etching steps are necessary. Xerographic stencilling was used primarily because of the speed of the operation. By this technique, resist images are formed on circuit plates in approximately two minutes. . . For applications where very high resolution (greater than 100 lines per in.) is required, photoresist methods are recommended.

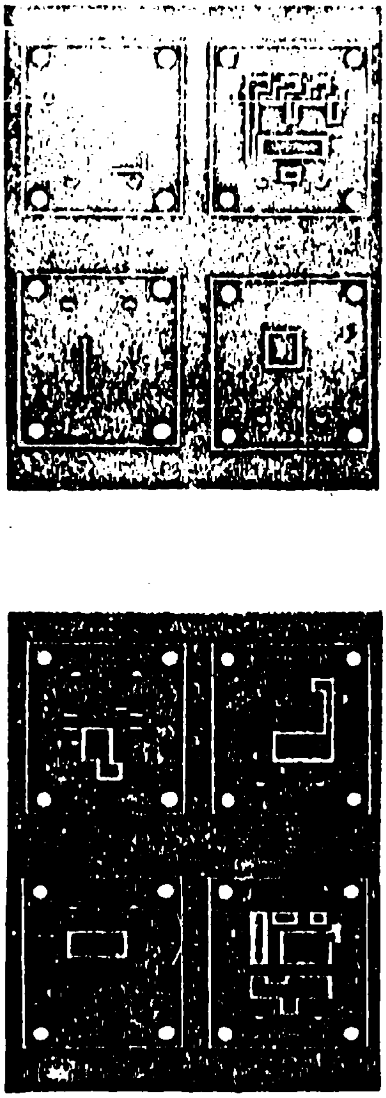
"Figure 3B shows the stencilling and etching steps necessary to form a simple flip-flop circuit from an RC circuit plate. The initial step consists of depositing on the conductive film a resist image corresponding to the conducting line-capacitor top plate electrode pattern. This is followed by an etching step which removes the exposed conductive material but does not attack the underlying film. Resistor formation is accomplished by an additional resist deposition, followed by an etching step that removes the exposed resistive film. Removal of the resist material completes the circuit. Note that it was not necessary to etch the dielectric film in order to form capacitors. As the capacitance of a parallel plate capacitor is proportional to the area of the smallest electrode, capacitance values within a particular range may be determined solely by the geometry of the top electrode."

Another subtractive method for fabricating thin-film microcircuitry is described in a Stanford Research Institute (SRI) proposal to the Information Systems Branch of Office of Naval Research. The method is described as "microminiaturization using electronic machining/etching techniques" is currently under investigation at Stanford.

All steps of the SRI process are conducted within the confines of a specially constructed ultravacuum system capable of being evacuated to better than 10^{-9} mm Hg. The deposition and machining operations may be described in general terms as follows:

"1. A film of material is deposited on a clean, smooth surface called the substrate by means of either vacuum evaporation or vapor deposition techniques. The materials may be metals or non-metals, e.g., tungsten or aluminum oxide.

"2. By simultaneously exposing the deposited film to a low pressure decomposable gas and a localized electronic beam, a stable compound called a resist is formed where the beam hits the surface. Gaseous by-products



NAFI MASKS

FIG. 1

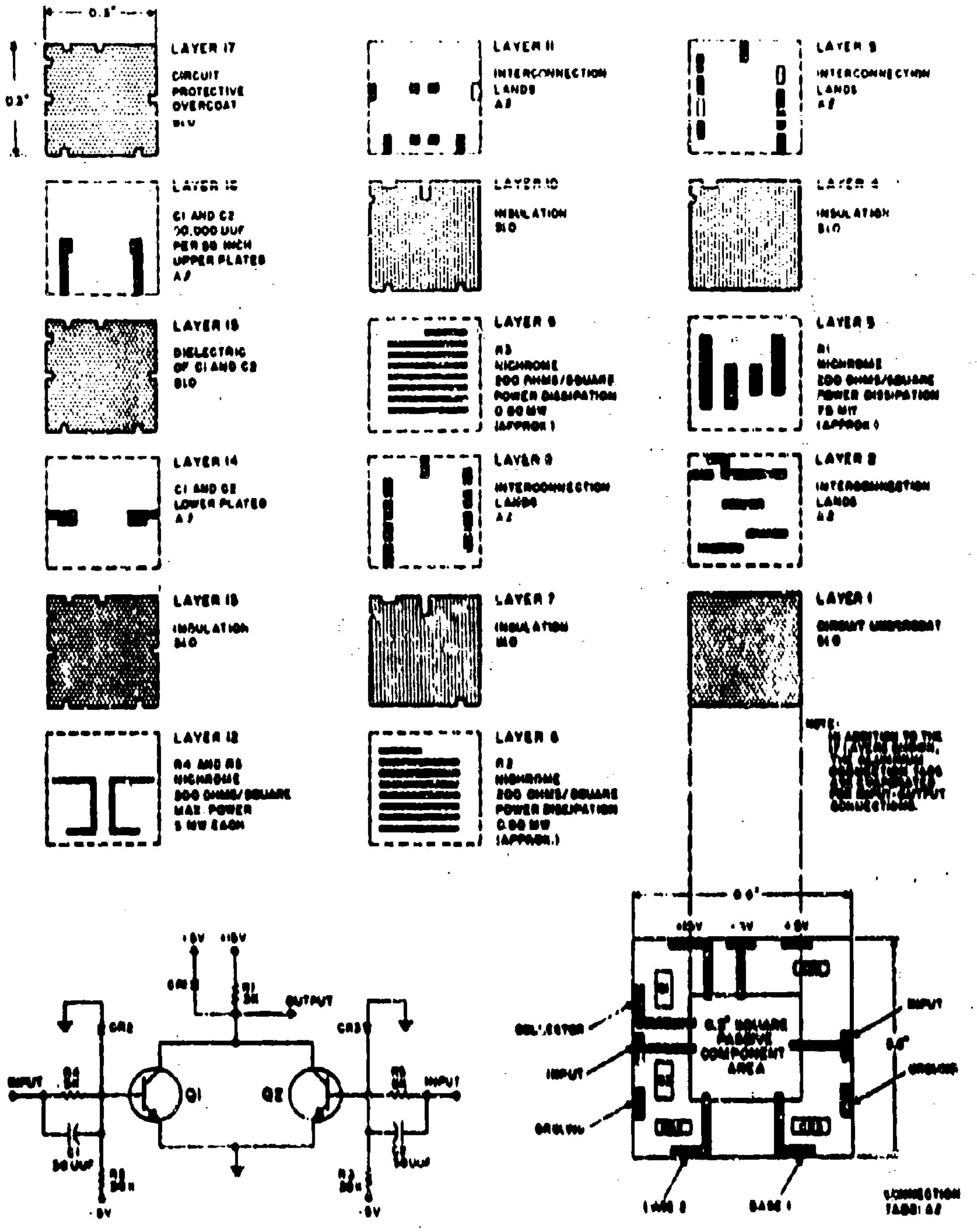


FIGURE 2 FILM LAYOUT FOR $\overline{\text{OR}}$ CIRCUIT (IBM)

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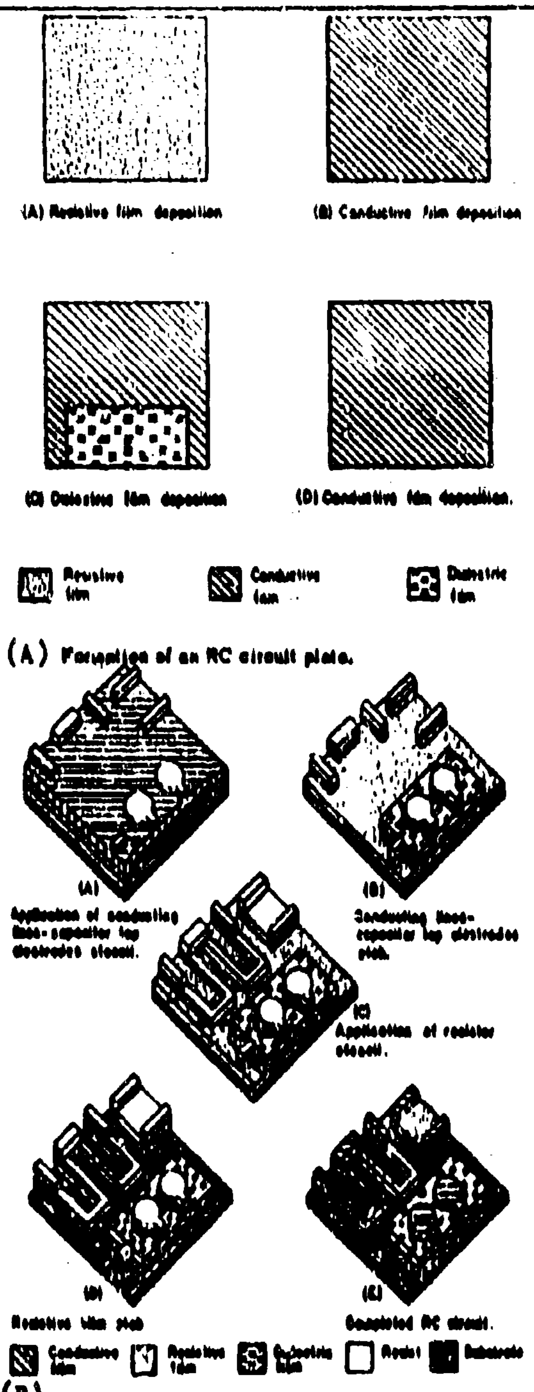

Fig. 3 Steps required to convert an RC circuit plate into an actual circuit.

(HALOID)

P.1 - 12 [illegible]

are pumped away. The resist will afford protection to the underlying film during a subsequent etching process.

"3. Etching is accomplished by raising the substrate temperature, and exposing the film to a gaseous etchant; a volatile compound is formed by reaction between the film and the etchant, while areas protected by the resist remain unaffected.

"4. The thin resist layer may now be removed by means of another gaseous etchant.

"The over-all result is the production of a pattern of material that has the shape of the electron beam. Simple spots, lines, or areas may be obtained by proper control of the electron beam. The maximum resolution is set by the resolution of the electron beam. Materials that have been processed by this method include molybdenum, tungsten, tantalum, silicon, iron, nickel, silicon dioxide, and aluminum oxide. A much wider selection of materials is possible."

Figure 4 shows the successive steps followed by Varo for depositing passive components and insertion of the active ones. Figure 5, left and right, respectively, present conventional and distributed parameter schematics of the same circuit. An important objective of the Varo program is to form components by means of ion beam deposition, thus eliminating the need for evaporation masks.

Arma has been forming thin-film circuitry on 1/2" square x .030" thick wafers as illustrated in Figure 6. Passive components are evaporated and transistors are inserted into .100" diameter holes, and the diodes into .060" holes.

Figure 7 shows an adder made by Aerovox. It consists of 7 wafers connected by means of a printed wiring ceramic board. Here, again, the passive components are either evaporated or printed while diodes and transistors are attached to the interconnecting wiring.

The Sylvania or glass hat, as it is frequently dubbed, uses hermetic sealing with an inert protective atmosphere. Exploded and completed views of modules are shown in Figure 8. Individual circuit wafers use a combination of evaporation and printed techniques to apply components. A significant feature claimed for this concept is: it uses no organic sealers or encapsulants. Interconnections are made by fired on printed wiring.

IRC has been supplying evaporated resistors and capacitors and has accumulated considerable data and much valuable experience in thin-film work.

DOFL is forming entire functional circuits on a single thin wafer. Thin-film components are deposited in a 2 dimensional form and uncased transistors and diodes are mounted in holes within the body of the wafer.

IRC, in addition to developing conductive, resistive, and insulating films, has fabricated integrated circuitry by mounting diodes and transistors in holes drilled through the substrates. Research and development work aimed at developing thin film active elements is currently under investigation.

B. MICROCARDS

There appears to be widespread misconception among casual readers concerning many of the aspects of microelectronics. A number of the misinformed associate high vacuum techniques with microelectronics. This association probably results from the publicity given to the commendable work of Varo Manufacturing Company, a pioneer in evaporated microcircuitry. High vacuum technique is only one way of depositing thin films and the thin-film concept is only one approach to microelectronics. The realization of the latest approach to microelectronics requires no expensive vacuum coating equipment. This relatively new approach, the simplest attempted thus far, is a refinement of conventional printed circuit board techniques to include the incorporation of microminiaturized circuit components. Many microminiaturized components (microcomponents) used are those developed for use in the U. S. Signal Corps - RCA micromodules. Other microcomponents have been developed or are being developed through the efforts of the Microminiature Electronic Components Group organized within EIA Engineering Department. This group is concerned only with discrete components at this time, and has specifically excluded pre-assembled groups of components in modular form.

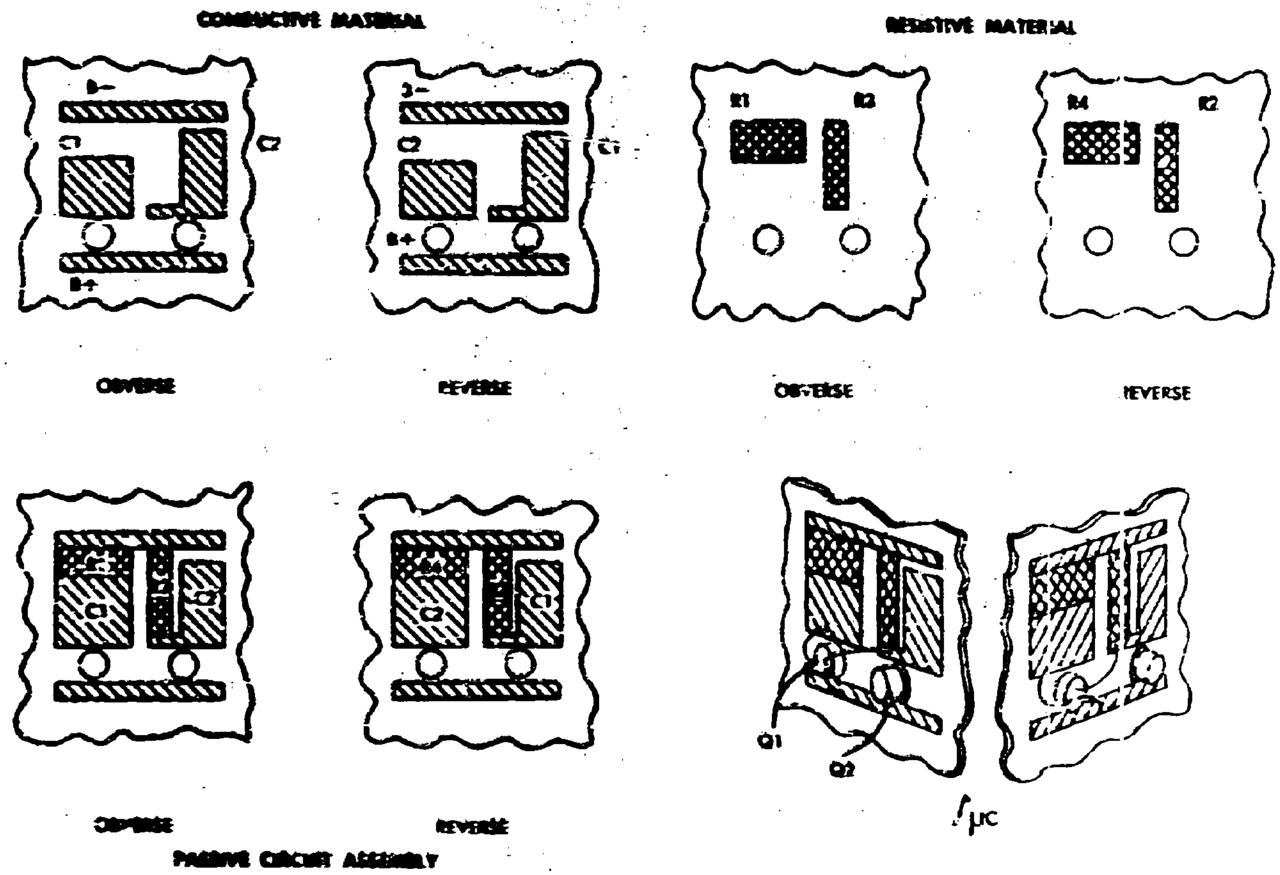

Figure 4. Morphology of a Typical Flip-Flop Circuit
(VARO)

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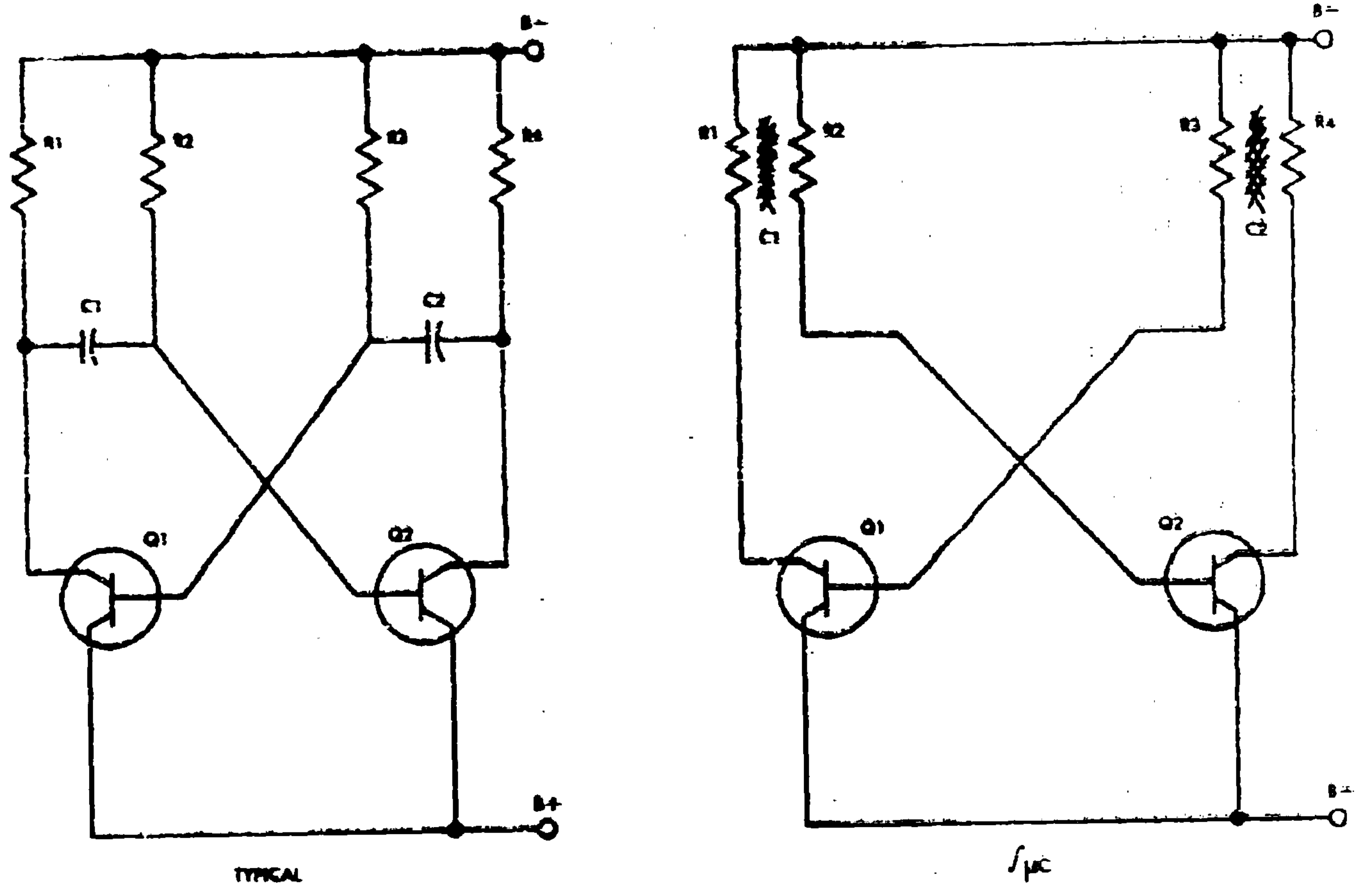

Figure 5 Conventional & Distributed Parameter Schematics of a Flip-Flop Circuit
(VARO)

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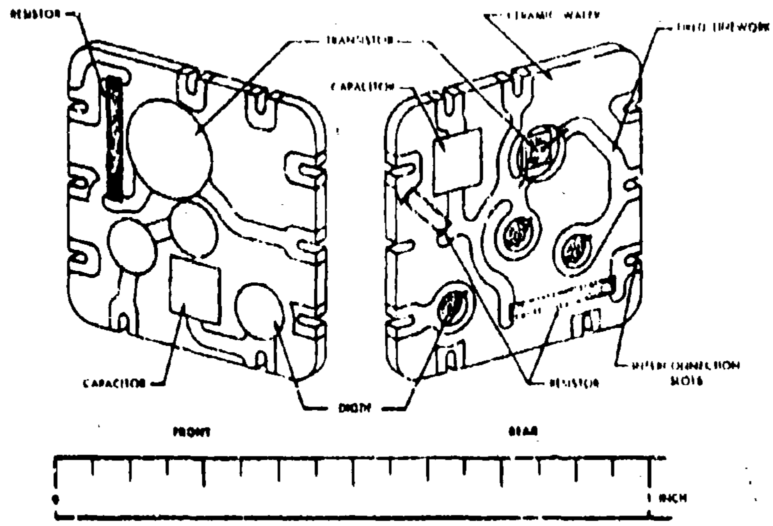


Single Flip-Flop Wafer Layout

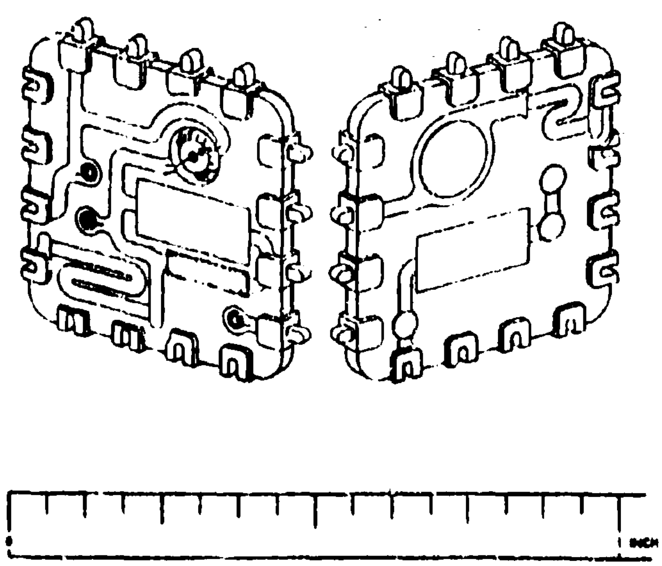


Fig. 6 Single Flip-Flop Wafer Layout by Vacuum Deposition
(ARMA)

AEROVOX CONCEPT

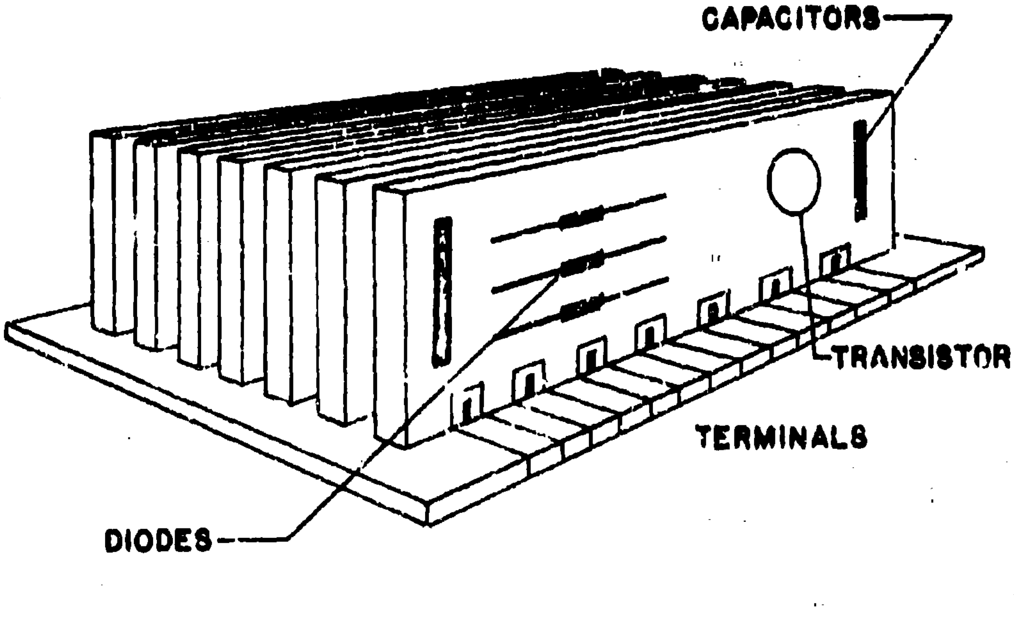
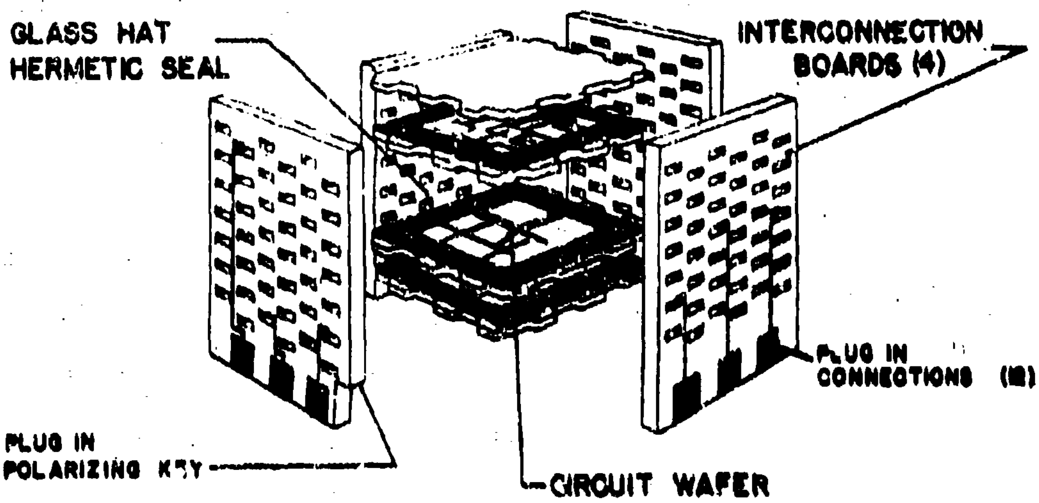


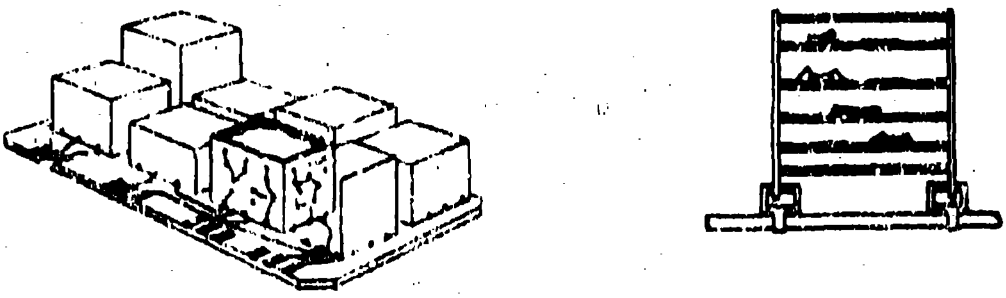
Figure 7

MODULE CONSTRUCTION

EXPLODED VIEW



INTERMODULE CONNECTION



(SYLVANIA)

Figure 8

The scope of the EIA Microminiature Electronic Components Group follows:

"To recommend physical and mechanical requirements for individual small reliable active and passive components as used in digital data processing systems. The particular areas of concern to be included are:

a. Recommendations of form factors and lead placement of components so as to facilitate the production of systems.

b. Recommend a set of specifications on components suitable to successful assembly with particular emphasis on environmental conditions.

c. Recommend the means for the handling and transportation of components from the supplier to the consumer."

This group has no illusions that the combination of printed circuit board techniques and microcomponents represents the ultimate in microelectrics. Rather, they recognize this approach as an interim step to be adopted until such time that thin film microelectronics and/or solid state circuitry are demonstrated to be reproducible, reliable, and economically acceptable.

The simplest version of the microcard consists of microcomponents with pigtail leads mounted on thin etched copper clad glass epoxy or Teflon boards. The fabrication of these microcards necessitates more care during the etching and assembly steps than is required of conventional printed circuitry. Cleveland Metal Specialties Company is one of the industrial laboratories sponsoring this concept.

Other methods for mounting microcomponents avoid the need for pigtail leads. In these packaging schemes the microcomponents are inserted within the body of a ceramic wafer which carries the associated circuitry on its two major surfaces.

The Ramo-Wooldridge packaging scheme (See Figure 9) - "involves the imbedding of presently available microminiaturized components in photo-etched cavities in a ceramic wafer. Copper-etched electrical conductors for interconnection are contained on the surfaces of the ceramic wafer which also acts as the structural carrier for the components. The present program uses discrete components, but can be extended to include micro-module units and molectronic units as they become available. Each wafer provides at least a circuit function. Several wafers are then interconnected, by a proprietary micro-connector, to perform a system function.

"Repair is affected by the two-level process currently used in digital equipment. Repair of the equipment is accomplished by interchanging plug-in carriers; the carrier is repaired by replacing parts. Although the carriers are initially dip soldered, parts can be removed by a soldering iron and a new part can be pushed in with little effort."

The Hughes' packaging concept of microcircuit boards (See Figure 10)

is - "centered about circuit elements, .050" diameter x .030" thick. Diodes, resistors, and capacitors in this form are provided with gold-clad end plates for attachment into the circuitry. Transistors would have the collector contact in a similar .050" diameter end plate, with emitter and base leads emerging in two plates on the opposite surface. Such components can be inserted within the body of a board which carries the associated circuitry on its two major surfaces. Devices are carried in .052" diameter through holes in a .030" thick substrate and the holes are located on a .100" square matrix. Such spacing is adequate for inter-component connection, yet is not so tight as to present problems of accidental short circuits."

Neither of the packaging methods described above specifies standard substrate dimensions other than thickness. Indeed, it is claimed that to specify substrate area would destroy some of the flexibility in design claimed for these packaging schemes.

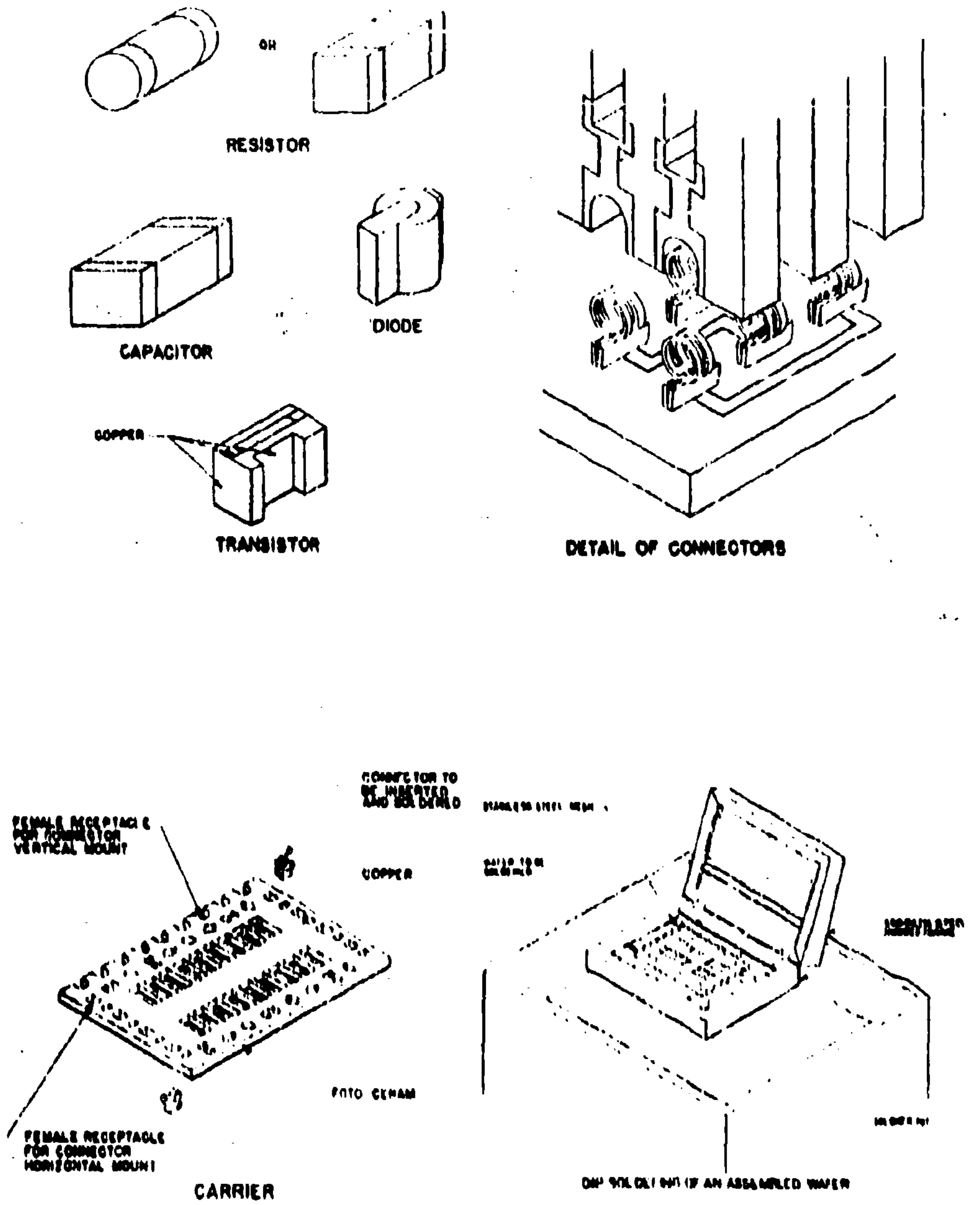
The Burroughs Corporation "Macro-Module" packaging concept of microcircuit boards (See Figure 11) specifies substrate dimensions. However, their scheme possesses a feature that may compensate for the inflexibility in design introduced by standardization of wafer dimensions. Unlike other packaging schemes, the Burrough's Macro-Module provides for the incorporation of a heat exchanger as an integral part of each module. The heat exchanger is said to provide efficient transfer of heat from the source to a sink.

The Burroughs Macro-Module wafer is a triangular chip one inch in height and 1.75 inches along its base. The first chips were fabricated by conventional printed circuit techniques. Later, chips were made of Corning Fotoceram with microcomponents mounted therein in a manner suggested by the Ramo-Wooldridge concept.

The Daven Division of General Mills has proposed mounting RCA microelements on large ceramic wafers to form functional circuitry. The aim is to eliminate difficulties arising from the use of riser wires normally used in the micro-module packaging concept.

The present state-of-the-art does not permit the fabrication of thin-film diodes or transistors by methods compatible with the deposition of passive components and interconnecting circuitry. Consequently, thin-film circuit fabrication requires that slots be formed in the substrate wafer to accommodate the active components. The proponents of microcircuit boards claim that the cost of providing additional slots or holes for the passive components is slight. In other words, they argue that as long as active components have to be imbedded in the substrate wafer all the components might as well be imbedded. The added cost of providing more slots or holes to a wafer, it is claimed, is more than compensated by the savings resulting from the elimination of critical masking problems and expensive vacuum operations.

The proponents of microcircuit boards enumerate other advantages of this concept of microcircuitry as compared to evaporated circuitry. Among these advantages they list:



RAMO-WOOLDRIDGE CONCEPT

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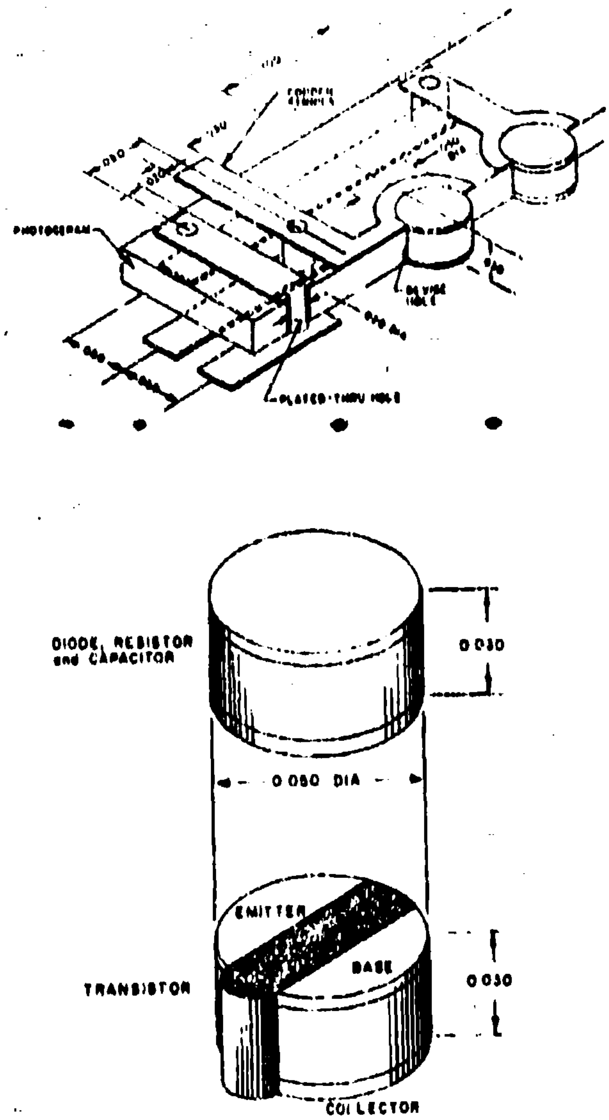

HUGHES CONCEPT

Figure 10

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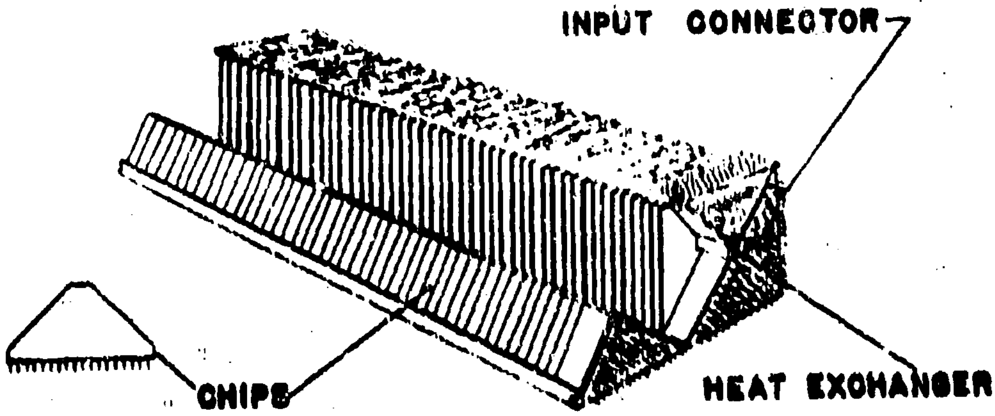
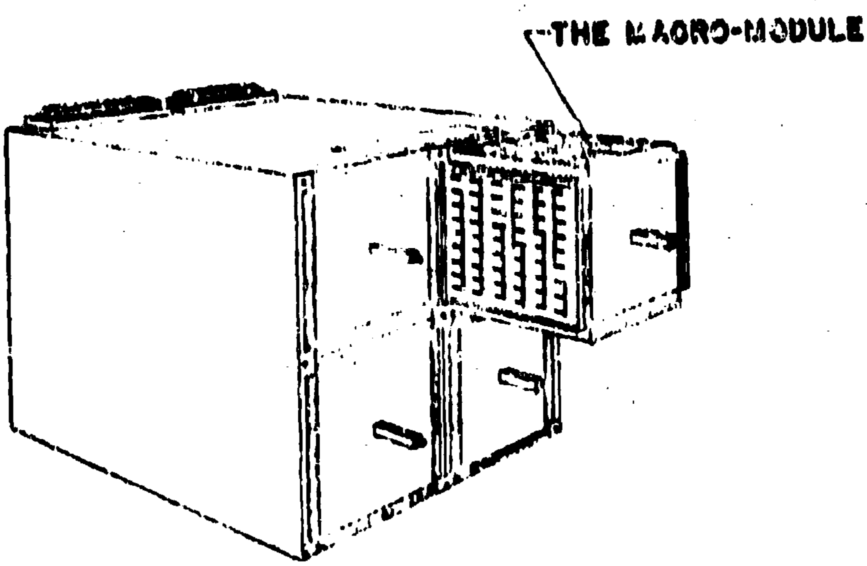
THE MACRO-MODULE





(BURROUGHS)

Figure 1

a. Lower investment in capital equipment. No costly high vacuum equipment is needed.

b. Lower operating expenses. Lower level of skills required and non-critical operations required for fabricating microcards.

c. Lower design costs.

d. Higher wattage rating of resistors. The wattage rating of inserted resistors average about twice that of evaporated thin-film resistors.

e. Higher resistances and greater capacitances per unit surface area.

f. Closer tolerances on resistors and capacitors. These components may be pre-selected according to their values.

g. Wider range of circuit components can be accommodated. Ceramic, electrolytic and tantalytic capacitors, wirewound, carbon and other resistors, and inductors may be inserted in microcards. Also, solid circuits developed by Texas Instruments and others can be imbedded in ceramic substrates.

h. Greater yield. Since components are individually pre-tested before imbedding a 100% yield can be expected. A mishap during any one of the several deposition cycles for producing an evaporated circuit invalidates the entire wafer.

i. Repairable. Microcards can be repaired. A mal-functioning component can be unsoldered and replaced. Evaporated circuitry cannot be repaired.

j. Microcomponents for insertion into holes in substrates are available and can be supplied to order. Special sizes and shapes of substrates can be fabricated or purchased. Microcard-type integrated modules could be put into production at this time. This conclusion cannot be reached for thin-film techniques at this time.

k. In general, size of components and substrates could be "standardized" for many current endeavors, thus bringing automatic assembly one step closer to reality.

The volume occupied by a microcard consisting of components imbedded in a substrate is comparable to that occupied by a four-layer thin-film circuit.

Following is a quotation from a recent advertisement describing another approach to microminiature circuitry called MICRAM (Microminiature Individual Components Reliable Modules):

"The combined technology of five companies has resulted in high reliable, off-the-shelf components which can be packaged in standard modules or to specific requirements with a density of 2 million components parts per

cubic foot. MICRAM has made these components and modules available to industry today - not a promise for the future. Hi-Q Division, Aerovox Corporation; CMS Cleveland Metal Specialties, Co.; PSI, Pacific Semiconductors, Inc.; Raytheon Company; and Sylvania Lighting Products. Capacitors Hi-Q, Photo-engraved "Printed" circuits, Designs & Packaging from Electronics Division of CMS Co., Diodes from PSI, Transistors from Semiconductor Division, Raytheon Co., Readout & Indicator Lamps from Sylvania Lighting Products, division of Sylvania Electric Products, Inc.

The Signal Corps-RCA Micromodule[14] concept is an extension of the Tinkertoy module concepts developed at the Bureau of Standards. Instead of developing integrated stages on a single substrate, each component is held by a separate one. The individual wafers with their components are stacked and connected by riser wires through notches along the edges to form complete stages. The inference is that components can be made up ahead of time and stored for future use. Individual wafers are .31 inches square by .02 inches thick.

A unique concept by G. E. is illustrated in Figure 12. Components are formed about standard toroids made of a high titanium-ceramic body. Assembled units are hermetically sealed at a low pressure, are rugged, and quite resistant to the effects of radioactive fields. These units are said to operate successfully at 500°C, and once operating temperature is attained, heaters, as found in conventional electron tubes, are no longer required.

C. SOLID CIRCUITS

"With the advent of the transistor and the work in semiconductors generally, it now seems possible to envisage electronic equipment in a solid block with no connecting wires. The block may consist of layers of insulating, conducting, rectifying and amplifying materials, the electrical functions being connected directly by cutting out area of the various layers." This prophetic quotation by G.W.A. Dummer in 1952 just about summarizes some of the recent accomplishments of solid state circuitry.

Work in this field is being pursued by a number of laboratories. Some are working on individual components, while others are working on complete stages. (See Figure 13) As indicated above, the introduction of the transistor greatly accelerated research in solid state physics.

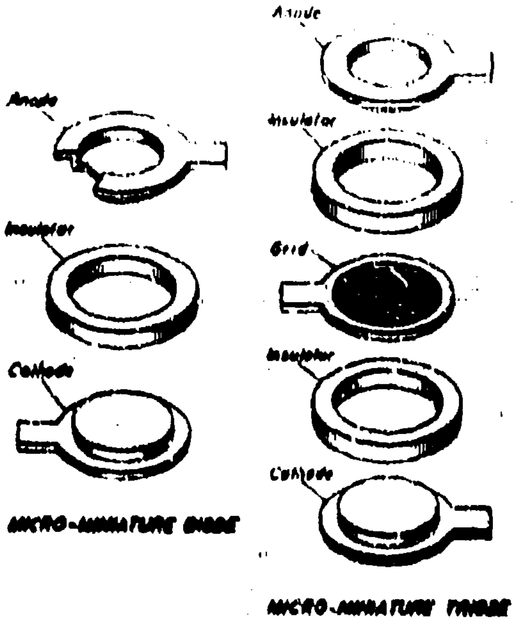
Principle objective of solid state circuitry is to perform all circuit functions within a properly prepared crystal of a semiconductor. A crystal might perform one of the following circuit functions:

a. R.F. Amplifier

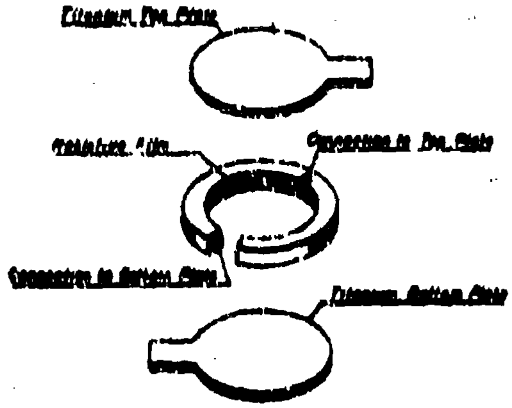
b. I.F. Amplifier

c. Oscillator

d. Mixer



Exploded views of micro-miniature titanium-ceramic diode and triode.



Exploded view of micro-miniature titanium-ceramic resistor.

Figure 10
(U)

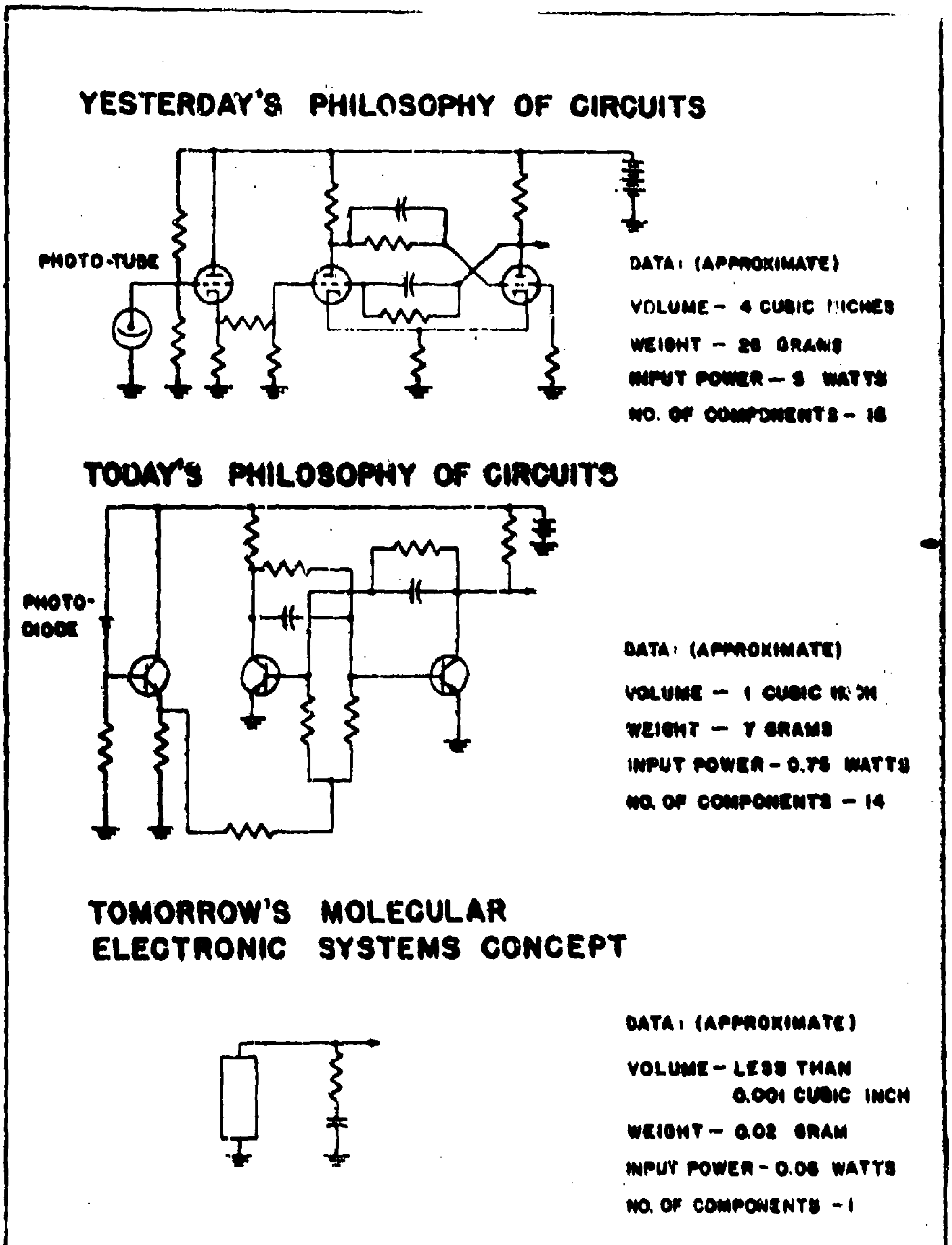


Figure 13
(WESTINGHOUSE)

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e. Power amplifier

f. Logic

Molecular engineering, as such, is being pursued by a number of laboratories, notably, Westinghouse, T.I., Bell Laboratories, Sylvania, Sperry-Rand, and Varo. One, or a combination of the following techniques, is used in molecular engineering; etching, diffusion, vapor deposition, ion bombardment, zone melting, etc. In other words, any technique that allows one to have control over the arrangement of the molecules in a substance is classified as molecular engineering.

In spite of the excellent work that has been done, all workers agree there is much more to be done before it will be ready to emerge from the laboratory. While much of the theory is fairly well established, there are a few nebulous areas requiring more study and research. Exclusive of research, the greatest need is in the field of applied development. This involves the application of new methods and techniques and the adaptation of methods from other sciences. As a matter of fact, the fabrication of solid state devices requires some knowledge of a host of sciences and arts, some of which may not be related to each other, and requires change in thinking, etc. Some units are available, but it may be 1970 before completed units are commercially available.

Solid state functional blocks, products of a new science called "molecular engineering" are being exploited by several laboratories. A working model of an audio amplifier was recently demonstrated publically. Its fidelity was "mediocre" but it was spectacular in that the unit was about the size of a pencil eraser. To a casual observer it resembled a piece of anthracite with several wires attached. As more basic knowledge of the physics of the solid state is acquired, it is anticipated more sophisticated devices will become available.

Parallel with these endeavors, a strong materials program is required to develop lesser known materials able to function in high ambient temperatures, and to handle greater power.

It is possible that a small piece of suitably prepared silicon or other semiconductor material will replace several circuit components. The desired impedance, capacitance and inductance in an amplifier stage may be designed into a single solid state device.

The Westinghouse molecular engineering approach takes advantage of the advances made in quantum mechanics in recent years. A proprietary method of growing dendritic crystals in the form of ribbons having very flat surfaces is reported. So far three-zone dendrites have been produced and demonstrated. One objective is the development of solid state functional blocks.

Molecular system engineering differs greatly from all other microminiature concepts in that individual, or conventional, components cease to exist as such. Equivalent electrical functions are performed by properly

doped and grown domains usually within a solid crystalline block of a semiconducting material.

Another approach though not proprietary starts with a thin wafer of a uniformly doped or undoped semiconducting crystal. Then by various surface treatments such as etching, diffusion doping, vapor plating, etc., the various active and passive component areas are formed in place. Soldered connections and interconnection wires are entirely eliminated.

Figure 14 shows a full wave rectifier constructed on diffused silicon wafers with a slit and trough design. Its size is about 1/4 x 1/2 inches.

Figures 15 and 16 show the general layout of the Sperry-Rand and Arma concepts respectively.

Single crystal silicon ingots are now available and can be furnished in several specified resistivities. These can be sliced, diced and formed into diodes and transistors by several methods such as alloy junction, surface barrier, diffused base and alloy-diffused base. These techniques avoid the problems associated with the grown junction crystal and eliminate high scrap losses. These units can be prepared in advance or formed in place if required. This concept is illustrated in Figure 17.

Much more research and development work is required before units of this kind will be ready for the production line. The state-of-the-art is in such a flux that one cannot, with any degree of certainty at this time, predict what the ultimate morphology will be. After reviewing the current literature, however, one or two trends seem to be emerging. One obvious one is that electronic assemblies will continue to shrink in size and weight. Also efficiencies will continue to increase. As more fundamental knowledge of the physics of the solid state is gained and applied, more "breakthroughs" can be expected. Each step forward is bound to have its influence upon the size and form of the final product.

Dr. Harper Q. North, president, Pacific Semiconductors, Inc., has this to say about solid state circuitry: "It's a wonderful concept degraded by over-publicity and about to experience retardation . . . as a result of over-optimism. When technology catches up with it, we'll be able to strive toward brain-like circuitry with a vengeance. I'm guessing it will take five years or more."

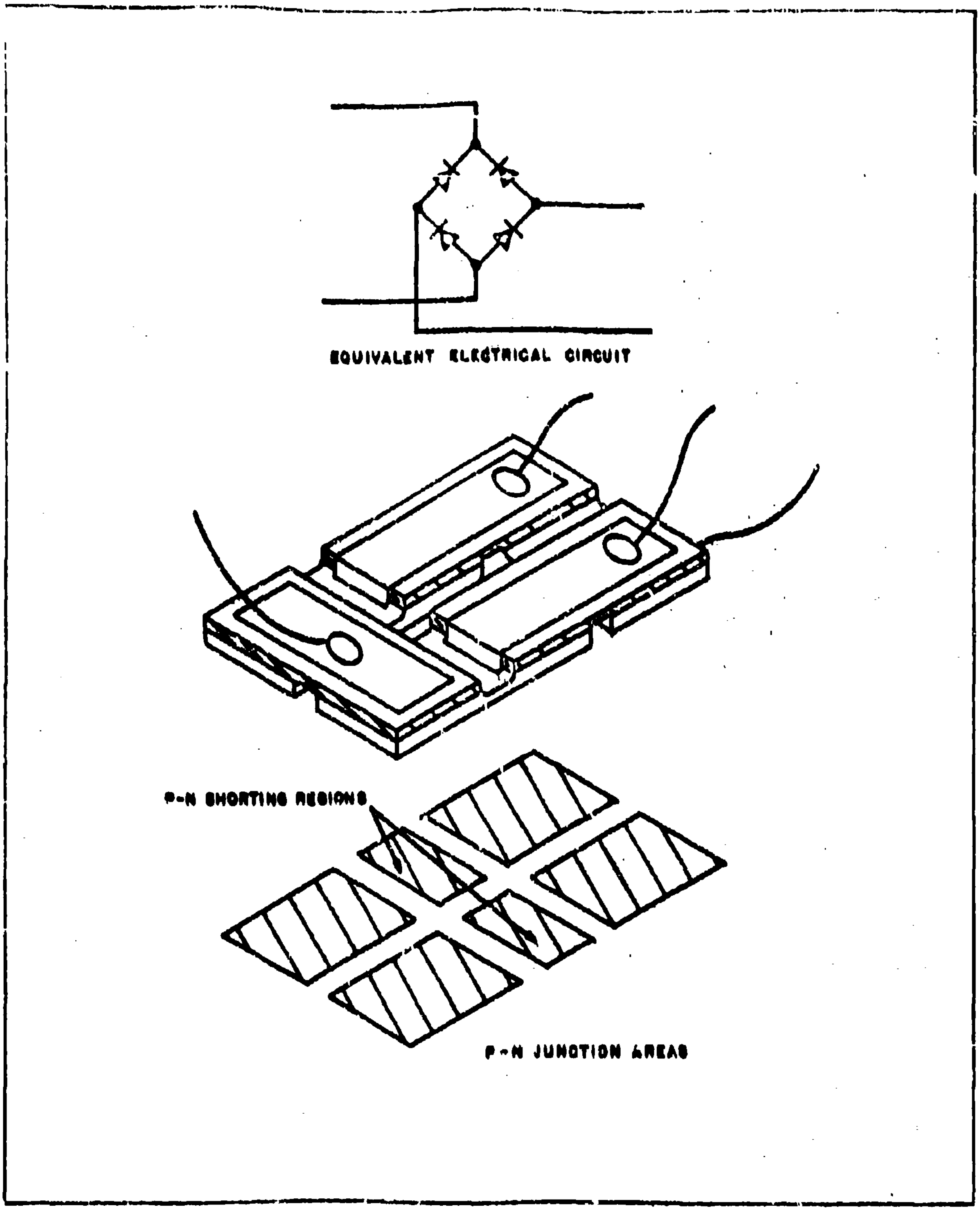

Figure 14 Full-Wave Bridge Monolithic Design
(WESTINGHOUSE)

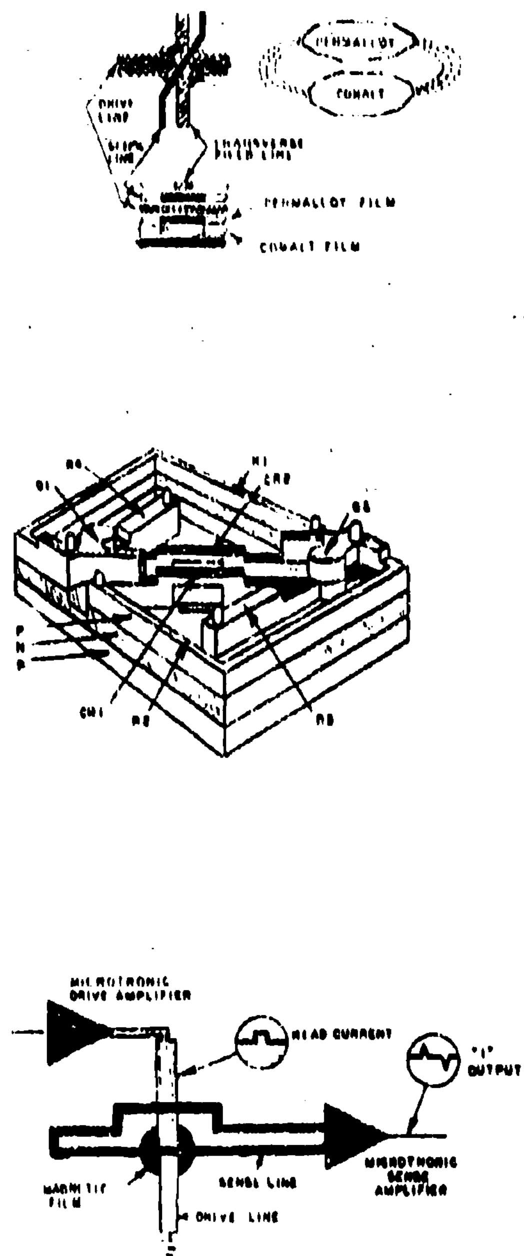

FIG 15
(SPERRY-RAND)

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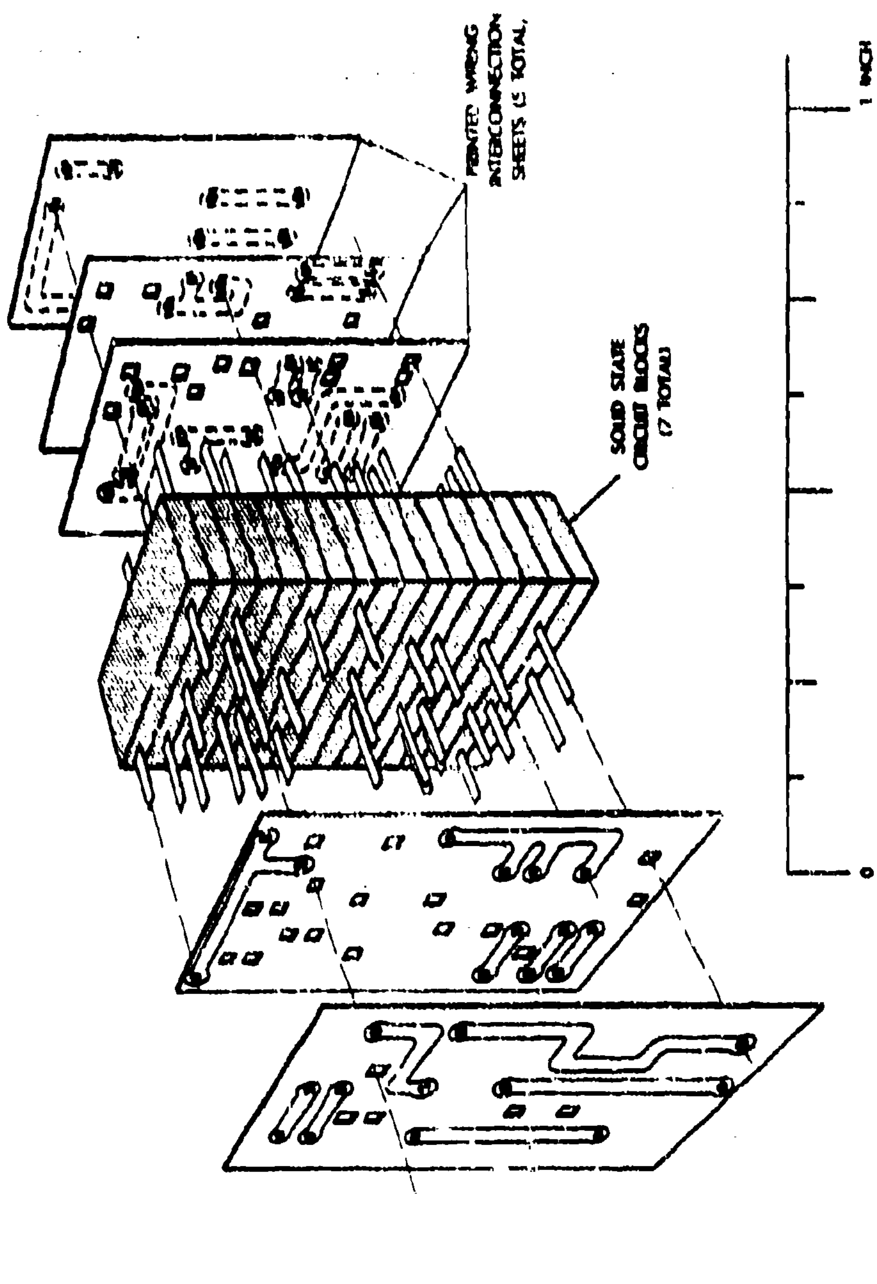


Figure All Solid State Hermetically Sealed Adder Assembly

([illegible] FOR ABMA)

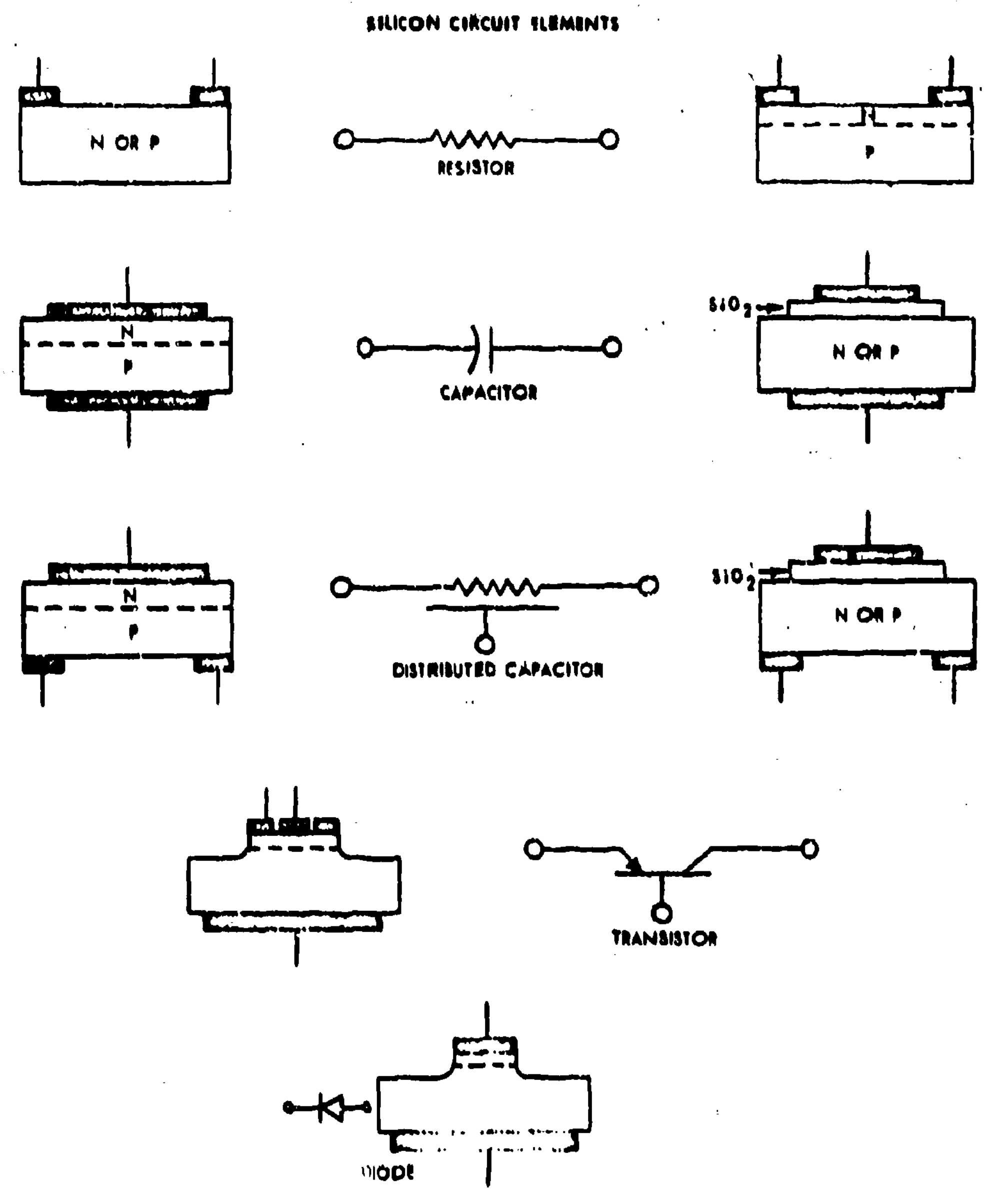


Figure 17 Silicon Circuit Elements

V. MATERIALS AND TECHNIQUES FOR THIN FILM MICROCIRCUITRY

The present state-of-the-art of thin-film microcircuitry fabrication permits the deposition of resistors, capacitors, small inductances and their interconnecting conductor lines on glass, fused silica or ceramic substrates. Ultimately it is hoped that semiconductor materials can be deposited in proper crystalline structure and in correct amounts so that semiconductor devices, such as diodes and transistors, can be formed integrally with the circuit.

A. METHODS OF DEPOSITING THIN FILMS

Thin solid films can be produced by a number of different methods, including:

a. Electro-deposition

b. Chemical precipitation, notably of copper, silver and nickel

c. Thermal decomposition (vapor plating)

d. Solid-state reactions, including "burning on"

e. Cathodic sputtering

f. High vacuum evaporation

Although all of these methods have been exploited to some degree in attempts to develop thin-film microcircuitry, high vacuum evaporation is the most popular. In general, films deposited by high vacuum evaporation have higher purity and the process is more easily controlled.

1. High Vacuum Evaporation

High vacuum evaporation is simple in principle. (Fig.18) It consists of raising the temperature of a thermally stable material in a vacuum so that evaporation takes place. The evaporated material is emitted in straight lines from a heated source and condenses on to surfaces surrounding the source. Some materials evaporate from the liquid phase while a few, notably chromium, evaporate or sublime from the solid phase.

There are three common methods for heating an evaporant, namely: resistance heating, r-f heating and electron bombardment.

B. RESISTANCE HEATING

Resistance heating is the cheapest and most readily available means of raising the evaporant (source material) to its evaporation temperature. In this method the material to be evaporated is heated in contact with a refractory metal, such as tungsten, tantalum or molybdenum, through which a current is passed. The source heater may be in the form of a boat,

crucible, or filaments as shown in Fig. 18. A disadvantage of this method is that many materials, when heated to evaporation temperature, react with the boat material. This reaction results in the evaporation of the boat material as a film contaminant and also causes the boat to eventually "burn out". These deficiencies can be avoided in some instances by heating the evaporant by radiation (Fig. 18E) or by using a crucible that does not react with the material to be evaporated (Fig. 18D).

Control of source temperature for resistance heating may be accomplished with a variable autotransformer (Variac). This control is fast and accurate and serves to closely control the rate of evaporation.

1. R-F, or Induction, Heating

R-F, or induction heating of evaporation source material is caused by coupling r-f energy from a coil of a high frequency generator to the evaporant. This energy may be coupled directly with a conductive evaporant or with a conductive container holding a nonconductive source material. This method of heating, which may be controlled quite closely as to source temperature, permits fast evaporation. Induction heating is superior to resistance heating in that no new impurities are introduced into the system. Contamination is absent for a nonconductive evaporant if it has a melting point sufficiently lower than that of the conductive container. The chief disadvantage of induction heating is the high initial cost. Some of the industrial laboratories using r-f to heat evaporants are: Bell Telephone Laboratories, IBM, Remington-Rand Univac, and Hughes Aircraft Company. (Fig.19)

2. Electron Bombardment Heating

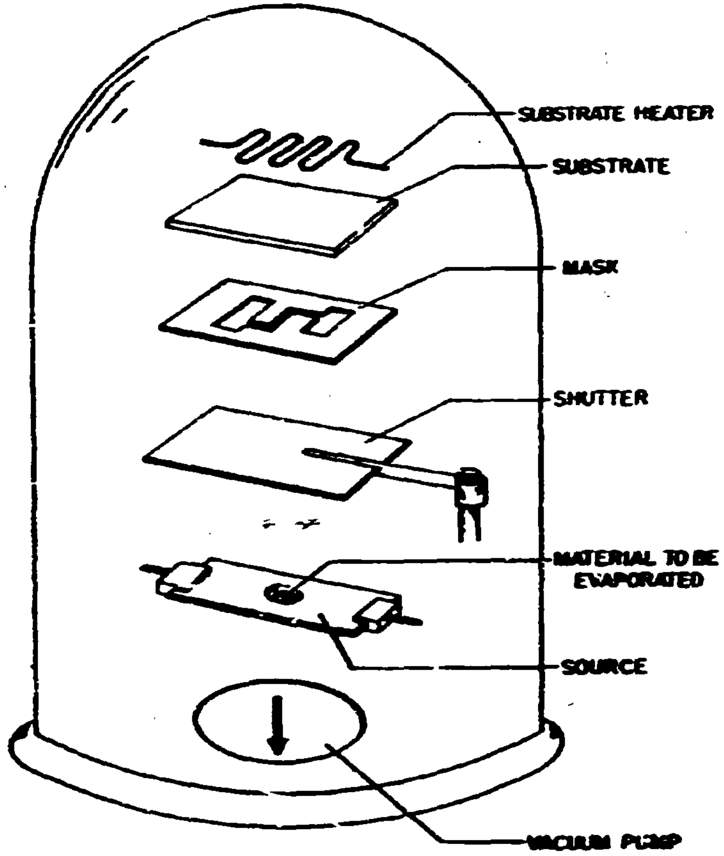
Electron bombardment melts target anodes of x-ray tubes and burns holes in the plates of vacuum diodes if heat is not dissipated. When properly controlled, electron bombardment is a highly satisfactory method of heating an evaporant.

The essential elements of an electron bombardment arrangement (see Figure 20) are a cathode (heated filament) and anode (usually a metal to be evaporated) plus power supplies. When heated, the filament emits electrons which are accelerated to the anode by potentials between 1,000 and 10,000 volts.

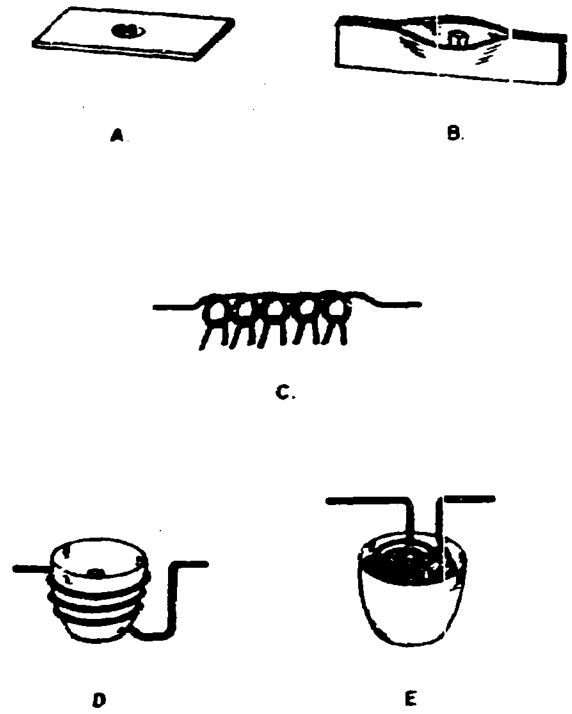
Some of the industrial laboratories using electron bombardment heating are: Varo, IBM, Motorola, and Halex.

3. Cathode Sputtering

The cathode of a glow discharge slowly disintegrates during bombardment by ionized gas molecules. Some of the atoms ejected from the cathode condense on surfaces surrounding the cathode. This method of obtaining a metallic film is called sputtering. Although this coating method has been known for a long time, the mechanism of the process is not fully understood. The sputtering process requires a range of pressures from 1 down to about 10^{-2} mm Hg. and a range of potentials from 1000 volts to as



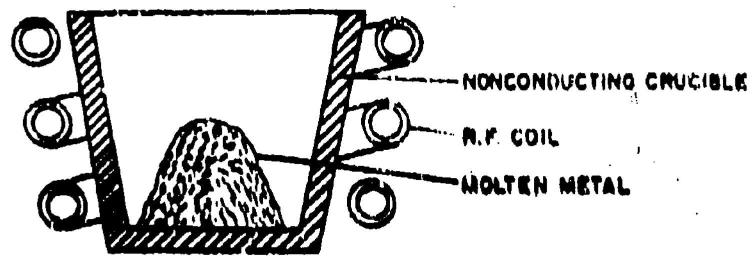
EVAPORATION PROCESS



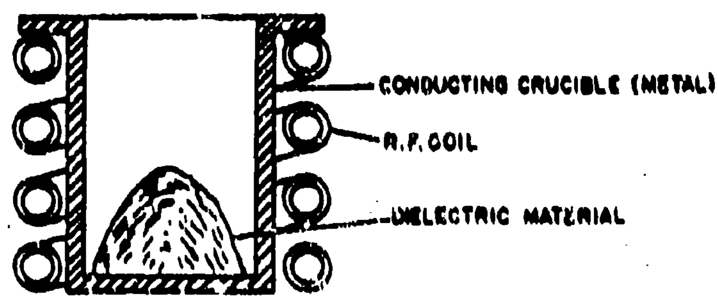
RESISTANCE HEATING OF EVAPORANT

Figure 1[illegible]

INDUCTION HEATING OF EVAPORANT



A.



B.

FIG. 19

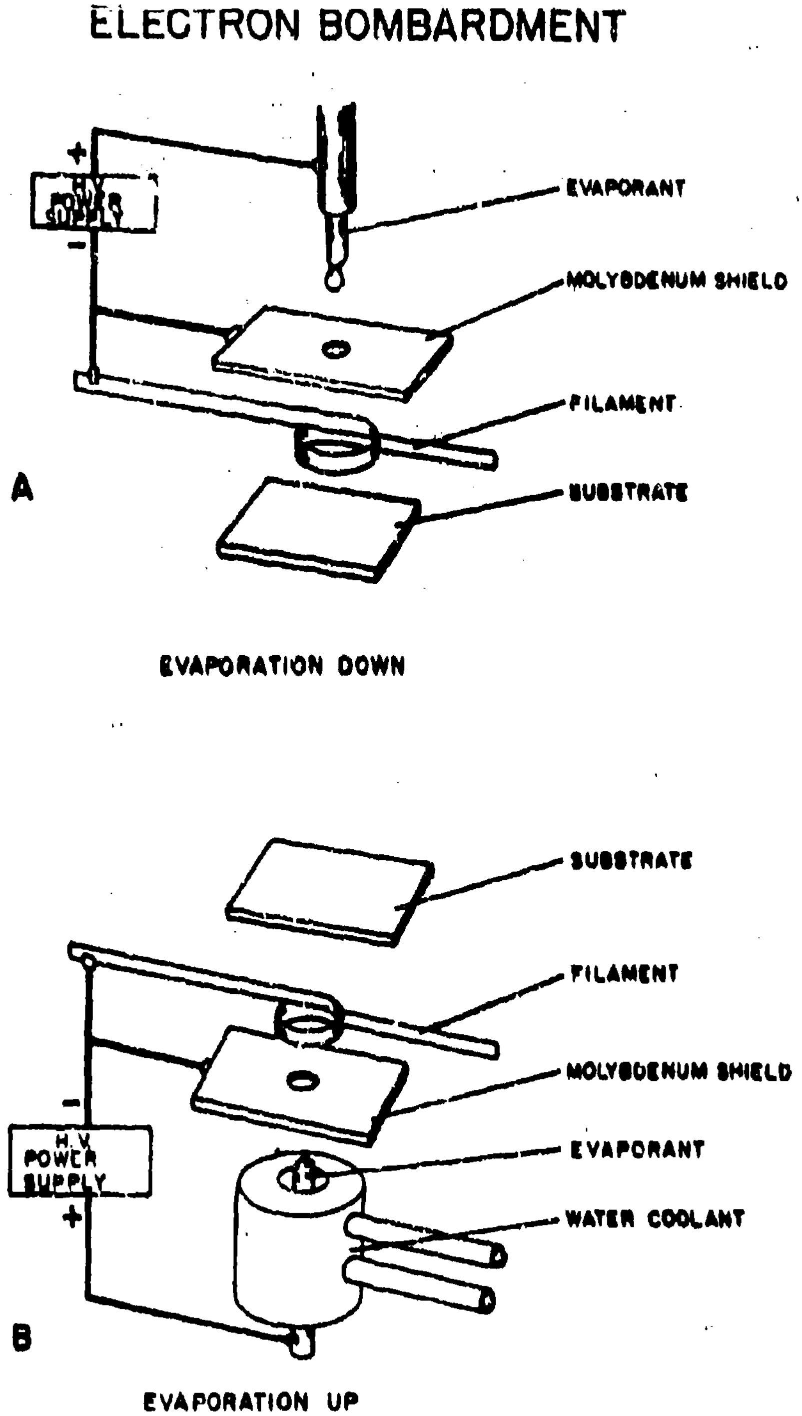

ELECTRON BOMBARDMENT
+
H.V. POWER SUPPLY
-
EVAPORANT
MOLYBDENUM SHIELD
FILAMENT
A
SUBSTRATE
EVAPORATION DOWN
SUBSTRATE
FILAMENT
MOLYBDENUM SHIELD
-
H.V. POWER SUPPLY
+
EVAPORANT
WATER COOLANT
B
EVAPORATION UP

FIG. 20

high as 20,000 volts. The sputtering process for depositing thin films is normally much slower than high vacuum evaporation. Some metals are deposited at faster rates than others. Bismuth, silver and gold sputter much faster than metals such as chromium, aluminum and titanium, which are protected by refractory oxides. The sputtering rate also depends on the gas in which the glow discharge occurs. The rate is relatively high in argon and lowest in helium.

Sputtered films rarely have properties superior to those of evaporated films. A notable exception is the greater adherence of sputtered gold films. Since sputtered films are produced in a poor vacuum, they are likely to be contaminated by occluded gases. For this reason and because sputtering is a much slower film producing process, high vacuum evaporation is generally preferred.

Bell Telephone Laboratories[36] employ cathode sputtering in a circuit fabrication concept involving the use of a single refractory metal, such as tantalum or zirconium, to form conductor lines, resistors, capacitor electrodes and capacitor dielectric. Since refractory metals readily oxidize in a glow discharge, the coating chamber has to be purged of oxygen. Purging is accomplished by reducing the coating chamber pressure to below 10^{-6} mm Hg and flushing with pure argon. The sputtering operation is performed in argon. Bell Telephone Laboratories recommend high vacuum evaporation with electron bombardment heating as being superior to cathodic sputtering.

Cathodic sputtering normally requires a gas pressure a few orders of magnitude higher than can be tolerated during vacuum evaporation; however, a high vacuum sputtering process was demonstrated by the General Mills Company laboratory. Their process requires that the substrate to receive the coating be immersed in a low-pressure plasma of high density.

As mentioned, some metals readily oxidize in a glow discharge. The process whereby a conductive material reacts with an ionized gas in a glow discharge is called reactive sputtering. For example, barium titanate, rendered conductive by reduction in a hydrogen atmosphere, will produce barium titanate films when sputtered in the presence of oxygen. Other conductive materials may be sputtered in various active gases to form compounds. In general, reactive sputtering of films is slow and difficult to control. Much work remains to be done before the process is made practical for microelectronic applications.

4. Methods of Heating Substrates

Means to achieve rapid and uniform heating of substrates are necessary for the economical production of stable evaporated thin film circuitry. The most common methods for heating substrates are: infrared heating units directed toward the face of the substrate, resistance contact heaters placed above the substrate, and a d.c. glow discharge from a cathode consisting of a metal having a low sputtering rate. The ion bombardment of the glow discharge not only heats the substrate, but also cleans it of hydrocarbons and moisture. However, since a glow discharge cannot occur in

a high vacuum, a special vacuum procedure must be followed. First, the evaporator is evacuated to coating pressure and air, or preferably oxygen, is admitted until the gas pressure is sufficient to sustain a glow discharge. A discharge of from 2000 to 5000 volts from 50 to 200 milliamperes for from 3 to 10 minutes is applied. Finally, the evaporator is evacuated to coating pressure. Since there is an appreciable lapse of time between the end of the glow discharge cycle and the beginning of the coating cycle, the substrate has a chance to cool somewhat. Since the time required for pumping down to coating pressure may vary from cycle to cycle, the coating temperature of the substrate cannot be accurately predicted. Hence, the glow discharge method of heating is not suitable when a predetermined substrate temperature is required.

A convenient method for heating substrates is furnished by resistance heaters placed above the holders. Bare tungsten strips, coils or heating units consisting of tungsten wire imbedded in fused silica tubes have been successfully used for heating substrates.

Another convenient method for heating substrates is provided by infrared heating units with suitable reflectors to give uniform heating.

A discussion on evaporated films would not be complete without a few words concerning the structure of surfaces and the formation, structure, and adhesion of evaporated metal films. First of all, it should be noted that no surface is either smooth or uniform over areas measured in terms of atomic or molecular dimensions. The cleavage planes of crystals probably have the smoothest natural surfaces. Fire-polished borosilicate glass probably has the smoothest surface likely to be encountered in microcircuitry fabrication.

Borosilicate glass is composed essentially of silica (SiO_2) with varying amounts of boric oxide (B_2O_3) phosphorus pentoxide (P_2O_5) and alumina (Al_2O_3). Interspersed within the network are alkali or alkaline earth metals such as sodium and calcium. These elements are called network modifiers.

The building unit of silica glasses, which is identical to that of crystalline quartz, tridymite, cristobalite, and all silicates, is the SiO_4 tetrahedra. It is probable that the silicon and oxygen are only partially ionized and that their tetrahedral arrangement may be the result of the combined influence of the size of the silicon and oxygen ions and of the tetrahedral covalent forces. According to the rules governing glass formation these tetrahedra may share corners but not edges or faces, and at least three corners of each tetrahedra must be shared. From these rules, it is evident that the tetrahedral framework must include relatively large holes bounded by oxygen ions. The larger network modifying alkali ions may be found in these holes.

The structure of the surface of glass necessarily differs from that of the interior. When a piece of glass is cut, broken, or ground, chemical bonds are broken. If an Si-O bond is severed, oxygen from the atmosphere (or even oxygen in the partial vacuum of a high vacuum evapora-

tion chamber) almost immediately combines with the silicon. Therefore, the surface of a "clean" piece of borosilicate glass contains oxygen ions, many of which are attached to only one silicon ion, and chance sodium and other metallic ions. The unshared oxygens are said to possess unsaturated valences. Hence, the glass surface possesses regions of low and high surface activity. If clean glass is allowed to remain in the atmosphere of the laboratory for a short time, these unsaturated valences (points of relatively high activity) become satisfied by attracting hydrocarbons (oily molecules) or water.

Hydrocarbons can be removed from a glass surface by chemical methods. Water or the hydroxyl (-OH) ions can be removed by subjecting the glass surface to a temperature of about 400 C, preferably in a vacuum.

The points of relatively high energy existing on a clean glass surface become nucleation centers for condensed atoms during the vacuum evaporation process. The atoms to first condense on a glass surface migrate to points of higher energy and form isolated agglomerates or grains. The arrival of subsequent atoms causes these grains to grow together to form larger crystals and a continuous film. A hot substrate imparts more energy to a condensed atom than does a cool base, thus allowing the atoms to diffuse over the surface to form larger grains. Larger grains are also formed at slower deposition rates because the condensed material has more time to migrate over the surface to preferred sites.

A slow rate of deposition along with high residual gas pressure (poor vacuum) results in the formation of rough, porous, impure films. Gases present during evaporation may be occluded within the film structure or chemically combined with the film material.

The angle at which evaporated material impinges on a substrate surface influences the texture of evaporated films. As the incident angle is increased, the impinging atoms are unable to penetrate the interstices between grains growing on the substrate. Consequently condensation is confined to the peaks of the larger grains and growth proceeds in the direction toward the evaporation source.

Scratched or abraded areas on a glass surface expose more nucleation centers and present various aspects to the evaporation source. For these reasons surface asperities are magnified by evaporation of a material thereon. The same arguments explain why thicker films are rougher.

C. SUBSTRATE MATERIALS

The validity of a vacuum evaporated thin-film circuit is influenced by the mechanical, chemical, thermal and electrical properties of the substrate and the condition of its surface.

Plastics and other organic materials are undesirable, chiefly because they outgas in a vacuum and have poor thermal properties. Because of their high electrical conductivity, bare metals cannot be used as substrates; possibly, advantage could be taken of their high thermal conductivity by precoating them with a thin insulating film.

The macrostructure of the surface of a substrate affects the properties of an evaporated film. For example, the degree of roughness of a substrate influences the resistance properties of a film deposited thereon. On a rough surface, flat areas of peaks and valleys receive deposits at normal incidence, while steep sides are coated at oblique angles and thus receive a thinner layer. Hence, the film consists of a network of low and high resistance areas. Since most resistor films oxidize to some extent, the high resistance areas may consist predominantly of an oxide. Many oxides have a high negative coefficient of resistance while metals have a positive coefficient. Mixing the two effects may or may not have a desirable influence on the resistance characteristics. In any case the resulting properties may be difficult to predict.

The microstructure of the surface of a substrate also affects the properties of an evaporated film. From the nature of the growth of single crystals, it is known that the growth of subsequent layers tends to assume the same crystallographic orientation as the base crystal. This epitaxial growth on the surface of a non-oriented polycrystalline substrate is important in determining some of the properties of evaporated films.

An ideal substrate would have the following properties:

a. High thermal conductivity

b. Minimum electrical conductivity

c. Low thermal coefficient of expansion

d. High resistance to chemical effects

e. High mechanical strength

f. Flat, smooth surface for deposition

g. Homogeneous surface microstructure

h. Low dielectric constant

Of course no single material possesses all the desirable qualities listed above. Certain compromises appear to be necessary. Glass and some ceramics meet many of the desirable characteristics.

Glass is probably the most popular substrate material for evaporated thin-film microcircuitry. Although it has relatively low thermal conductivity, glass is cheap, readily available, has a flat, smooth surface, and has favorable electrical, chemical and thermal expansion properties.

The homogeneity of glass surfaces can be improved by evaporating thereon a film of silicon oxides from 2000 A to 10,000 A thick. Glass surfaces thus treated behave similar to fused silica, another substrate material of interest in microcircuitry fabrication.

Ceramics would be preferred for substrate wafers if they could be produced with dielectric constants as low as that of glass and surfaces as smooth as that of polished glass. In general, ceramics excel glass in heat conductivity, mechanical strength, and high temperature capabilities. Among ceramics of interest are high alumina (96% Al_2O_3) beryllia (BeO), barium titanate ($BaTiO_3$), Fotoceram and Fotoform. The latter two are of unique interest because precise intricate holes or slots can be formed in them by a patented photo-chemical process. However, Fotoceram and Fotoform are proprietary (Corning Glass Co.) materials, and hence their universal adoption for microcircuitry applications is unlikely.

Barium titanate ceramics would appear to be undesirable for use as microcircuitry substrate material because of their high dielectric constants (k greater than about 400). However, Varo Mfg. Co. has capitalized on these high dielectric constants and is successfully using barium titanate ceramics in a circuit concept involving distributed constants (Figure 5) as opposed to lumped circuit parameters. This circuit concept reduces the number of circuit components and roughly halves the number of evaporation masks required for producing R-C networks. Barium titanate ceramics suffer from extreme brittleness, a characteristic that may exclude them from serious consideration as microcircuit substrates.

Alumina and beryllia have many characteristics that make them attractive as substrates for microcircuitry. They have good overall thermal, electrical, chemical and mechanical properties and can be produced with a smooth surface texture. High beryllia ceramics possess all the desirable properties of the aluminas with respect to electrical, chemical and mechanical characteristics, but also have a thermal conductivity approaching that of aluminum metal. Beryllia, however, is toxic. When in a powdered form and in a condition which allows it to be taken into the lungs, beryllia can be a dangerous poison. No harm will result if simple precautions of adequate ventilation are observed during drilling or grinding operations on beryllia wafers.

D. MASKS AND MASK-SOURCE CHANGERS

The capacitance of a thin-film condenser is a function of the areas of the capacitor electrodes. The resistance of a thin-film resistor is a function of the resistor length : width (aspect ratio). The interconnection of microcircuit components requires the deposition of conducting materials on accurately located areas of the substrate. Hence, the successful production of passive thin-film microcircuitry is largely dependent upon the ability to deposit desired materials at accurately defined areas on a substrate.

Some types of masks are disposed of after use while others are used repeatedly. A disposable mask can be made from Kodak Photo Resist (KPR) in the following manner:

a. Coat substrate wafer with a thin film of KPR solution by brushing, spraying, or dipping. Allow film to dry.

b. Expose coated wafer to ultraviolet light through a photographic

positive of the circuit element.

c. Develop exposed wafer thus displaying the bare pattern of the circuit element.

The required material is deposited over the entire wafer by physical means (evaporation or sputtering) or by chemical deposition. The coated substrate is then immersed in a solvent for the photoresist. The photoresist with its overlay of deposited material is removed, except where the substrate was bared.

Photoresist does not make an ideal mask. Being organic it can degrade the vacuum in the case of evaporated films or it can contaminate sputtered films with its decomposition products. Also, if glass substrates are used, internal reflection of light during exposure (Step b) results in circuit patterns showing feathery edges.

These deficiencies can be avoided by adopting a more elaborate procedure for making disposable masks. In the modified process the substrate wafer is coated with a thin layer of metal, such as copper or aluminum, before proceeding with steps (a), (b), and (c). Following step (c) the bare metal is etched through to the substrate. The remaining layer of KPR is dissolved away, thus leaving an extremely thin metal stencil of the desired pattern firmly attached to the substrate. The material of the circuit element is deposited onto the etched metal pattern and the whole unit is immersed in an etchant for the metal. The metal mask with its overlay of deposited material is removed, leaving only the desired circuit element on the substrate.

Bell Telephone Laboratories pioneered the development of disposable metal masks. It is reported they produce patterns as narrow as one mil spaced one mil apart by using photoengraving techniques on sputtered copper films.

Because they are thin and maintain intimate contact with the substrate, disposable masks are capable of being fabricated in intricate patterns having extremely fine definition. Despite these attractive features disposable masks will probably not find extensive use in microcircuitry production. The rather complicated processes required for their fabrication and removal have to be repeated for each pattern. Because as many as four patterns are required for depositing circuitry on only one side of a substrate, great care must be taken not to damage any underlying films.

Although they are not capable of defining patterns of extreme detail, reusable masks are favored by most experimenters. Reusable masks are made of metal or etchable photosensitive glass. Masks fabricated from photosensitive glass have these attractive features:

a. They can be fabricated to extremely close tolerances (+0.0003 inch and -0.0000 inch) where necessary.

b. They are flat, rigid and are therefore capable of maintaining

contact with the substrate.

c. They will withstand considerable mechanical abuse.

d. They are unaffected by normal cleaning processes.

The chief drawback to the use of etchable photosensitive glasses are: they are proprietary products (Corning Fotoform and Fotoceram) and the time required for their fabrication and delivery can be an inconvenience.

Metal evaporation masks can be fabricated by machining, etching, or electroforming processes. Electroformed masks are usually formed on glass plates from which they are subsequently stripped. A typical procedure for manufacturing electroformed masks follows:

a. Evaporate a metal double layer - copper on aluminum - on a glass plate.

b. Coat metallized glass plate with a thin film of a photosensitive emulsion (such as KPR) by brushing, spraying or dipping. Allow photosensitive film to dry.

c. Expose sensitized plate to ultraviolet light through a photographic positive of the circuit element.

d. Develop exposed plate thus baring the metallic pattern of the circuit element.

e. Chemically etch away exposed metal.

f. Dissolve remaining emulsion layer (KPR) in a suitable solvent thus exposing the copper surface of the thin pattern of the evaporation mask.

g. Increase thickness of evaporation mask to about 0.002 inch by electroplating nickel from a nickel sulfamate bath.

h. Free evaporation mask from the glass plate by dissolving the aluminum underlayer in a suitable solvent.

The electroplating step reduces the width of openings in the mask because plating deposits metal at the edges as well as on the exposed horizontal surface. Hence, allowances must be made in the artwork to compensate for this deficiency.

There are several variations of the electroforming process. Masks having stencil patterns showing faithful reproduction of artwork can be electroformed by a process outlined in Section VI.

Most experimenters engaged in research on evaporated thin-film microcircuitry use etched metal masks from 0.0015 inch to 0.007 inch thick to define circuit patterns. Copper, iron, beryllium copper, mumetal, stainless steel and titanium are among metals from which masks may be etched. The

latter three are more desirable as they are more resistant to the corrosive action of cleaning solutions. However, this property that makes them desirable also renders them difficult to etch. Each metal requires a different etching technique.

Etched metal evaporation masks are fabricated by a photochemical-resist-etching process similar to a method commonly used for processing high quality double-sided printed wiring boards. A master pattern, which may range from 10X to 200X size, is photographically reduced to the size required for the finished mask. From this negative, a pair of film positives is prepared so that the patterns line up when their emulsions are placed together. Properly aligned films are taped together at two or three edges.

The sheet metal to receive the pattern is coated on both sides with KPR, or other photoresist emulsion, dried, and placed between the aligned films. This combination is placed in a vacuum frame and both sides exposed to ultraviolet radiation. After the coated metal is properly exposed, it is removed from the film envelope and developed in an appropriate solution. The exposed (hardened) emulsion acts as a resist in the etching bath.

The accuracy of the etched mask depends on a number of factors related to the etching process:

a. Speed of etch. In general, a faster etch will produce a more accurate pattern.

b. Ratio of metal thickness to opening width. Satisfactory results are obtained if the mask thickness is equal to the width of the narrowest opening.

c. Grain size of metal. A more accurate pattern having smoother edges can be etched from uniform fine grained metals.

d. Ability of photosensitive resist to adhere to metal. Obviously, poor adhesion of resist to metal would result in irregularities in the mask openings.

e. Homogeneity of metal. The rolling process used in fabricating sheet metal induces an oriented structural condition that causes preferential etching.

f. Etching procedures. For example, there is less undercutting of metal if the etchant is sprayed normal to the surface.

Regardless of the care exercised in etching masks, some undercutting always occurs. Openings in etched masks are always wider than the photographic pattern. Allowance for this discrepancy must be made in the artwork. The extent of the correction can only be accurately determined after etching procedures are established and measurements made.

Some experimenters have successfully used machined masks. A good jig borer such as found in a well equipped machine shop may be set up to

make several masks at one time. Several thicknesses of masking material of about 0.010 inch thick may be clamped together and machined simultaneously. Drilling and routing easily allow for rounds and circles to be designed into the pattern instead of squares and rectangles as with etched patterns.

Skilled operators are able to achieve tolerances as small as $\pm$ 0.0003 inch.

The deposition of an RC passive network usually requires evaporation through four stencilling masks from a minimum of three evaporation sources. A separate mask is required for each of the following: (1) resistors, (2) capacitor electrodes, (3) capacitor dielectries, and (4) interconnecting conductor lines and capacitor counterelectrodes. Separate evaporation sources are required for depositing (1) resistive films, (2) capacitive films, and (3) conductive films for electrodes and interconnections. An additional mask-source pair is required if a protective or encapsulating film is deposited over the circuit.

Batch coating requires a minimum of four pump-down cycles. Between each pump-down of the evaporator, masks, substrates and evaporation sources are changed. These operations require considerable manual labor and are time consuming. Furthermore, previously deposited films may become oxidized or contaminated. For these reasons, thin-film microelectronics will probably not gain acceptance in industry until active and passive components, their interconnecting lines and complete fabrication is accomplished in one vacuum cycle.

The state-of-the-art has not progressed to the point where this is practical. The first step in this direction is the development of mask-source-substrate changers to facilitate the deposition of passive circuitry in one pump-down cycle.

A suggested list of features that such a changer should possess are:

1. A minimum of three - preferably four or more - evaporation sources.

2. Evaporation source to be directly below substrate.

3. Evaporation source shutter mechanism operated by in-process monitoring system to control thickness of evaporated films, so as to achieve reproducibility of $\pm$ 5 percent.

4. Baffling to prevent contamination of sources by vapor stream from the other sources.

5. Sufficient number of masks to define a minimum of four circuit patterns on each substrate wafer.

6. Provisions for selecting and registering each mask to a tolerance of $\pm$ 0.002 inch on the substrate.

7. Provisions for assuring (a) intimate contact between the mask and substrate or (b) spacing of mask and substrate at a predetermined distance.

8. Provision for heating substrate to 360°C ± 10°C while it is in position to receive evaporated films.

Among industrial laboratories employing changers of varied degrees of complexity are: Varo, IRC, Hughes, Douglas, CBS Electronics and IBM. The latter two have the most sophisticated arrangements, but readily admitted they were not satisfactory for several reasons. In addition to mechanical problems there are those of monitoring, mask registration, and controlling temperature of the substrates.

E. RESISTOR FILMS

Resistors are the most widely used components in RLC networks. Considerable study is being conducted on resistive materials, processes and substrates upon which resistors are deposited for microcircuitry applications. Thin-film resistors may be fabricated in place on glass or ceramic substrates by a number of processes, which may be classified as: mechanical (injection molding and screen process), chemical (pyrolysis, hydrolysis and solid-state reactions) and physical (evaporation and sputtering).

Thin films suitable for microcircuitry resistor applications should be:

a. capable of being deposited in a reproducible manner, without resort to hand-trimming to meet resistance specifications

b. chemically inert to atmospheric gases

c. electrically stable

d. thermally stable

e. capable of adhering tenaciously to substrate material

f. relatively free of electrical and thermal noise

g. characterized by a relatively high resistance-per-square

h. endowed with coefficient of thermal expansion approximating that of the substrate material.

The Diamond Ordnance Fuze Laboratory (DOFL) has investigated the fabrication of resistors by applying resistor ink either by pen-type or screen-type printers. These methods are claimed to be satisfactory, but not as versatile as the injection molding process which allows for producing a wider range of resistances. DOFL has made thin-film resistors by high vacuum evaporation techniques and has also suggested the use of tape resistors. Electrical grade steatite wafers are used as substrates.

For several years high grade thin-film tin oxide resistors have been fabricated on glass substrates by the hydrolysis of tin chloride. These resistors are chemically and electrically stable and are capable of withstanding considerable mechanical abuse. Also, they have a low temperature coefficient and are relatively free from electrical and thermal noise. Tin oxide is normally an n-type semiconductor that can readily be doped with n or p-type materials to alter its electrical characteristics.

The resistance of tin oxide films depends upon a number of processing parameters. Only a few of the variables are normally controlled, consequently resistors made from tin oxide layers are usually selected from various lots according to resistance.

Recently Motorola (Phoenix) claimed to be able to control processing variables to such an extent that tin oxide films can be fabricated with a predictable resistance per square.

Bell Telephone Laboratories[36] produces up to nine microcircuit resistors on a glass or ceramic substrate by sputtering tantalum through a disposable mask. The tantalum films are stabilized by annealing in air. During this treatment the top layers of tantalum are converted to an insulating oxide and the resistance of the film is increased. Following this treatment the resistors are quite stable. An average change in resistance of about 0.2% in 800 hours at 100°C is reported for laboratory samples. The temperature coefficient of resistivity of these films is of the order of 100 ppm/°C as compared to approximately 3000 ppm/°C for bulk tantalum.

The resistance of a film produced in the manner described above is difficult to control. Hence, provisions must be made for hand trimming of resistors to desired values (See Figure 21).

Deposition by high vacuum evaporation appears to be the most popular method for producing thin film resistors for microcircuitry applications. A whole series of metals, semiconductors, and alloys have been studied for this purpose.

Nichrome[82] (80% nickel : 20% chromium) was one of the first alloys investigated and still remains the most popular material for thin-film resistor applications. Resistances of from 10 ohms per square to over 5000 ohms per square have been reported. Nichrome films showing less than about 20 ohms per square are so thick that they partially disintegrate. This breakup of the film is probably due to the difference between the expansion and conduction properties of the alloy and the underlying substrate. Nichrome films thin enough to show resistances greater than about 300 ohms per square normally do not exhibit the degree of stability desired for circuit fabrication. However, some industrial laboratories report the successful use of nichrome films showing resistances of 1000 ohms per square and even higher. Douglas Aircraft Company reports having made stable nichrome resistors showing resistances greater than 5000 ohms per square. These films were reported to have been stabilized in a helium atmosphere immediately after vacuum deposition.

Regardless of the monitored resistance of an evaporated thin nichrome film the resistance subsequently undergoes changes that may be quite pronounced. Immediately after the evaporation cycle the resistance of a nichrome film slightly decreases. This initial resistance decrease probably results from structural changes taking place within the film. The higher the substrate temperature, the less noticeable any initial decrease in resistance. The resistance of evaporated nichrome films begins to rise after any initial decrease in resistance. This increase in resistance results from a decrease in metal film thickness due to conversion of surface layers to a non-conducting metal oxide. The oxidation process and associated resistance increase proceeds slowly in the vacuum of the coating chamber. If air is admitted into the chamber shortly after the evaporation cycle, the nichrome film undergoes a rather large increase in resistance. After the resistor is removed from the chamber, its resistance slowly increases until a condition of stability is practically attained. The ultimate resistance and the time required for stabilization cannot, in general, be accurately predicted. For this reason, annealing or other treatments are resorted to, in attempts to stabilize the resistance of nichrome films.

Evaporated layers of silicon monoxide are sometimes used to protect resistor films. Generally, these layers are effective; however, the all too frequent presence of pinholes in evaporated layers of silicon monoxide will expose the resistor film to the air and allow it to oxidize or agglomerate. Better filming materials or improved evaporation techniques are suggested as remedies.

A different deposition sequence is usually followed when resistor films are coated with a protective layer. (See Figure 22). Frequently, the resistors are the first circuit elements evaporated. They are usually deposited on heated substrates and subjected to a subsequent heat treatment in vacuum before the remainder of the circuit elements are evaporated. The heat treatment causes an oxide film to form which is normally thin enough to allow adequate electrical contact to be made with the subsequently evaporated metal layers.

When protective layers are deposited on resistor films, the evaporation is normally made through the same mask that defines the resistor areas. Since protective layers are excellent insulators, films evaporated on to them cannot make electrical contact with the underlying resistor film. For this reason contacts for the resistors must be deposited prior to evaporating the resistor and protective films, as shown in method 1 of Figure 22.

Probably the present state-of-the-art of evaporated thin-film microelectronics permits the economical production of passive network circuitry consisting only of resistors and their interconnecting lines.

Even though considerable progress has been made in the development of evaporated resistive films, much research and development work remains to be done.

Areas of investigations in which resistor film improvements are required are: reproducibility, stability, resistance per square, temperature

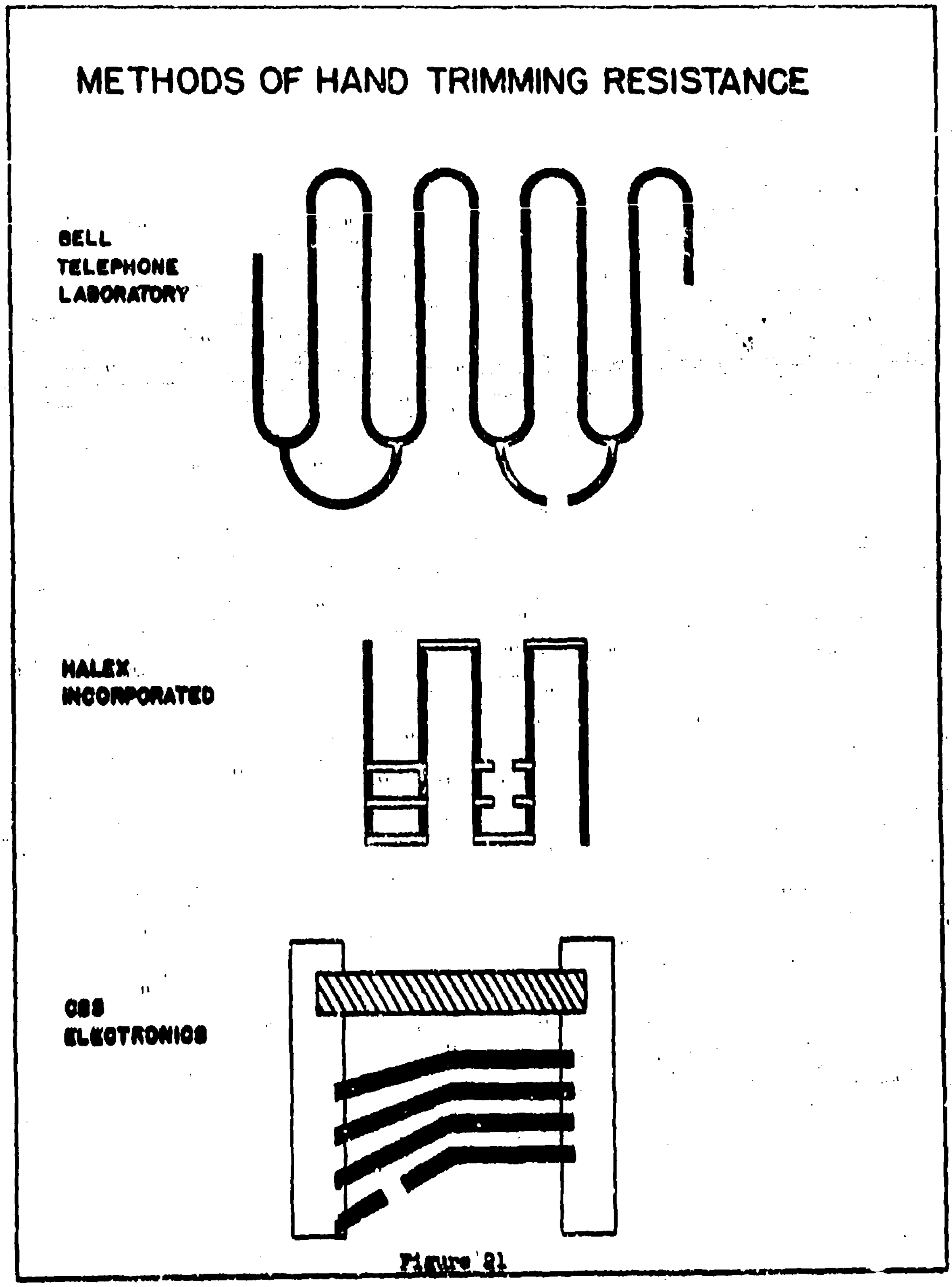

METHODS OF HAND TRIMMING RESISTANCE
BELL
TELEPHONE
LABORATORY
HALEX
INCORPORATED
CBS
ELECTRONICS

Figure 21

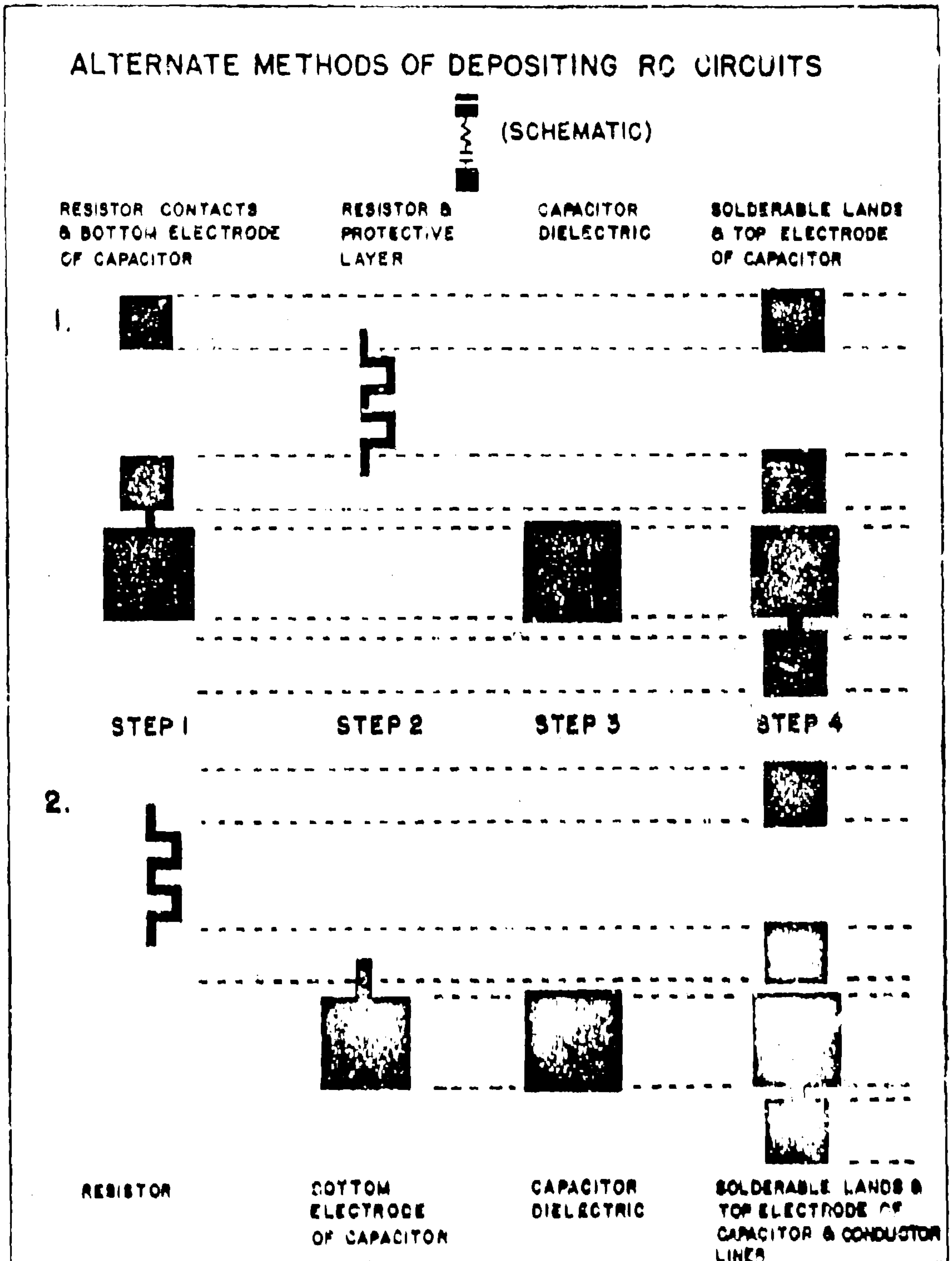

ALTERNATE METHODS OF DEPOSITING RC CIRCUITS
(SCHEMATIC)
RESISTOR CONTACTS & BOTTOM ELECTRODE OF CAPACITOR
RESISTOR & PROTECTIVE LAYER
CAPACITOR DIELECTRIC
SOLDERABLE LANDS & TOP ELECTRODE OF CAPACITOR
1.
STEP 1
STEP 2
STEP 3
STEP 4
2.
RESISTOR
BOTTOM ELECTRODE OF CAPACITOR
CAPACITOR DIELECTRIC
SOLDERABLE LANDS & TOP ELECTRODE OF CAPACITOR & CONDUCTOR LINES

Figure 22

dependence, and high temperature environment.

F. CAPACITORS

Capacitors can be formed in place on a glass or ceramic substrate by the alternate evaporation of metals and dielectrics. A capacitor of the simplest structure consists of two metal electrodes separated by a dielectric layer. The capacitance of such a structure depends upon the electrode geometries and thickness and dielectric constant of the interposing dielectric layer. For a given capacitor substrate area, the capacitance can be increased by making the dielectric layer thinner, increasing the number of metal-dielectric layers or by using a dielectric having a higher dielectric constant. The minimum thickness of a usable dielectric layer is limited by its dielectric strength. The addition of each metal-dielectric layer requires two additional mask-changing, source-changing evaporation cycles - a costly operation. Hence, the use of dielectrics showing higher dielectric constants appear to be the most satisfactory method of achieving higher capacitances.

Many of the light-transparent materials used for optical coatings have found favor as dielectrics for evaporated capacitors. Among these materials are silicon monoxide,[33] magnesium fluoride and zinc sulfide. Despite its relatively low dielectric constant (4 to 7.2) silicon monoxide appears to be the most popular dielectric for vacuum evaporated capacitors. This popularity is a result of the ease with which silicon monoxide can be evaporated and the glass-like character of the resulting films.

The composition and consequently the electrical properties of films produced from silicon monoxide starting material vary with rate of evaporation and the residual gas pressure. Films produced at a rapid rate in a poor vacuum or slowly in a good vacuum are predominantly silicon dioxide and exhibit the optical and electrical properties of silica. On the other hand, films produced rapidly in a good vacuum show optical and electrical properties approaching those of silicon.

The yield of capacitors by high vacuum evaporation is lower than one might expect. A major cause for rejection is "shorting" of the capacitor due to faulty cleaning, dust particles or "spitting" from the evaporation source. Despite all precautions to avoid surface contamination, pinholes continue to appear in dielectric films. The source, or sources, of these imperfections is not completely understood. However several experimenters have noticed that the number of pinholes per unit area of a dielectric film decreases with a decrease in coating pressure. This fact indicates that occluded gases may be responsible for the formation of some of the pinholes.

Short circuits in evaporated capacitors can be "burned out" by discharging a 4 mfd. capacitor across the electrodes.[41] This procedure, however, does not appear practical for production purposes.

Some experimenters have reported capacitor shorts due to the occurrence of weak points in the dielectric at the sharp step in the bottom electrode layer. Shorts due to this cause can be avoided by supporting the evaporation mask about 1 mm away from the substrate.[41]

Varo Manufacturing Company uses a technique, originating at Servomechanisms, for sealing pinholes in dielectric films with high resistivity silicon. Evaporated silicon behaves like a metal in that it has a tendency to diffuse over the surface of freshly evaporated SiO and fill the pinholes. The resistance of the silicon "shorts" in the silicon monoxide layer is too high to adversely affect the electrical properties of the layer.

If capacitors are formed by first evaporating a silicon monoxide layer over an aluminum electrode, pinholes can be sealed by a dichromate treatment or by anodizing the exposed aluminum in an ammonium tartrate bath.[32] There are other chemical and electrochemical methods that may be used to seal pinholes in capacitor dielectric films. Although these pinhole sealing methods are useful laboratory techniques, they do not appear to be satisfactory for use in production processes.

Among other evaporated capacitor dielectrics under investigation are boron nitride, calcium fluoride, aluminum oxide and some of the rare earth oxides and fluorides.

Silicon dioxide capacitor films can be produced by the pyrolytic decomposition of silicate vapors. Motorola (Phoenix) reports: "A capacitor was formed using the deposited SiO_2 film as a dielectric between two evaporated aluminum films. The capacitance area was one-fourth of a square inch and the dielectric thickness, as measured by sodium-light multiple-interference techniques, was between 1×10^{-5} and 1.2×10^{-5} inches. The capacitance measured 0.025 microfarads and the dielectric dissipation factor at 1000 cycles per second was 0.006. The dielectric constant of the films was determined to be approximately 4.5 which compares favorably with a k of 3.8 to 4.1 for quartz". TiO_2 films can be produced in a similar manner by hydrolysis of ethyl esters of orthotitanic acid. Techniques for producing these films on a production basis have not been reported.

Excellent capacitors can be produced by anodizing evaporated metal films and applying an evaporated counter electrode. Evaporated aluminum can be anodized in an ammonium tartrate bath[32] to form a pinhole-free hard adhering oxide film. The thickness of an oxide film produced by this method is 12.7A per volt. The dielectric constant is about 8.7. Capacitors produced by this method are currently being studied by the NAFI Laboratory.

Metals other than aluminum can be deposited on substrates and subsequently anodized to form capacitor dielectric films. Bell Telephone Laboratories are using deposited tantalum for this purpose. Capacitors are produced by anodizing sputtered tantalum films and applying an evaporated counter-electrode such as gold or aluminum. Capacitors for 50 volt operation have a capacitance of about 0.1 mfd/cm^2. The dielectric constant of anodic Ta_2O_5 is about 25 or about three times that of anodic Al_2O_3. However, the time consumed in processing a tantalum-tantalum oxide double layer is quite long. The sputtering time for depositing a tantalum film of suitable thickness is about an hour as compared to about a minute for evaporating an aluminum film. Thermal evaporation rather than cathodic sputtering would materially reduce the time required for depositing tantalum layers. An anodizing time of from one-half hour to 4 or 5 hours is required for forming

Pg 70-78

Ta_2O_5 layers for capacitor applications. Only about a minute is required for forming Al_2O_3 films of comparable thicknesses.

Because of its high dielectric constant titanium dioxide is a desirable dielectric for capacitors having microelectronic applications. Unfortunately TiO_2 partially dissociates when heated in a vacuum so that the resulting films consist of a bluish suboxide of titanium. Starting with a suboxide of titanium, the NAFI Materials Laboratory has evaporated colorless films in a poor vacuum in which the residual gas was oxygen. These films, which were assumed to consist essentially of TiO_2, will be studied with regard to their adaptability to microelectronics applications.

Ferro-electrics such as barium titanate and other titanates have high dielectric constants. These materials, like TiO_2, dissociate when heated in a vacuum. Servomechanisms, Inc. is experimenting with a reactive sputtering technique for producing films of $BaTiO_3$. The starting material is a thin plate of barium titanate ceramic (supplied by Mullenbach). The barium titanate is rendered electrically conductive by heat treatment in a hydrogen reducing atmosphere. The reduced barium titanate is made the cathode in a reactive sputtering chamber in which the residual gas is pure oxygen. Films resulting from this reaction show promise as a capacitor dielectric.

Films consisting essentially of barium titanate have been produced by evaporating reduced barium and titanium oxides from separate sources. The resulting films, which consist of a mixture of the suboxides of barium and titanium are oxidized by heating in air at a temperature above 450°C. Titanium films can be converted to TiO_2 layers by a similar treatment.

While many of the above mentioned methods of forming dielectric layers are suitable for use in fabricating isolated capacitors their application to microelectronics will require further study. For example, one critical problem in the formation of dielectric films is to control their thickness. This, plus the geometry and dielectric strength, determines the ultimate utility of the capacitor.

The fabrication of evaporated thin-film capacitors appears to be in a rather rudimentary stage of development. Because evaporated capacitors are difficult to fabricate, frequently exhibit "shorts", and show low capacitance per unit area, many experimenters resort to inserted ceramic capacitors.

Areas of investigations in which capacitive film improvements are required are: elimination of pinhole shorts, dielectric constant, dielectric strength, dielectric loss and fabrication techniques.

G. INDUCTORS

The fabrication of inductive devices by thin-film techniques presents problems in masking and involves evaporation sequences that are difficult to control. (See Figure 23). Only low value thin-film inductors have been made because of area limitations and the necessity of depositing them in a two-dimensional spiral. A flat spiral thin-film inductor of only

one microhenry consists of a seven-turn spiral 1/2 inch OD. x 3/8 inch I.D.

IBM reports the production of a two-dimensional spiral 10 microhenry inductor consisting of 46 turns of 0.002 inch conductors spaced 0.004 inch on centers. Fabrication of this inductor required successive applications of vacuum evaporation electrodeposition and photoengraving techniques.

The incorporation of inductors in microcircuitry should be avoided when possible. Such well-known networks as the twin T and various filters or RC coupled oscillators can often be substituted for inductors. Low frequency oscillators can be made by phase-shifting RC networks. Certain solid state devices, used in conjunction with more conventional circuit components, behave as virtual inductances in some circuits.

Even though inductors remain an anomaly, some promising work has been performed at the Signal Corps.[40] They have been able to synthesize inductors to a limited extent, by using RC networks with a negative-resistance diode. A germanium diffused-base transistor with an open-circuit base connection serves as the diode.

H. CONDUCTIVE FILMS

Conductive films are the least critical of evaporated circuit components and their deposition does not present many problems. The choice of conductor material is governed by a number of factors including adhesion to substrate and to adjacent layers, compatibility with materials of adjacent layers and method adopted for attaching leads of inserted components.

In general, metals that grow hard, adherent protective natural oxides adhere tenaciously when evaporated onto other metals and onto glass or ceramics. Among these metals are chromium, titanium and aluminum. However, because of their protective oxide coatings, it is impossible or extremely difficult to solder directly to these metals. On the other hand, metals that do not form protective oxide coatings adhere poorly when evaporated on to oxide protected metals, glasses, and ceramics. Among these are the easily soldered copper, gold and silver. These metals, however, form strong metallic bonds when evaporated onto unoxidized, clean metallic surfaces. Consequently a solderable surface can be produced on a glass, ceramic or other oxide coated surface by first evaporating a layer of chromium, titanium or aluminum and then evaporating a layer of copper, gold or silver. The sequence of evaporations must take place in the same vacuum and in rapid succession from adjacent evaporation sources. Any appreciable time lapse between the evaporation of the oxidizable and solderable layers results in the formation of an oxide barrier layer between the two. Even at pressures as low as 10^{-7}mm Hg there is sufficient oxygen to rapidly form an oxide barrier layer on some metals. Hence, the sure way to obtain metallic bonding, and therefore good adhesion, between two metals such as gold and chromium is to avoid a barrier layer by intermixing these metals at their interface. This is accomplished by first evaporating chromium and at the first visual indication of deposition bring up the gold evaporation while shutting down the chromium evaporation. The gold evaporation is continued until a satisfactory thickness is reached.

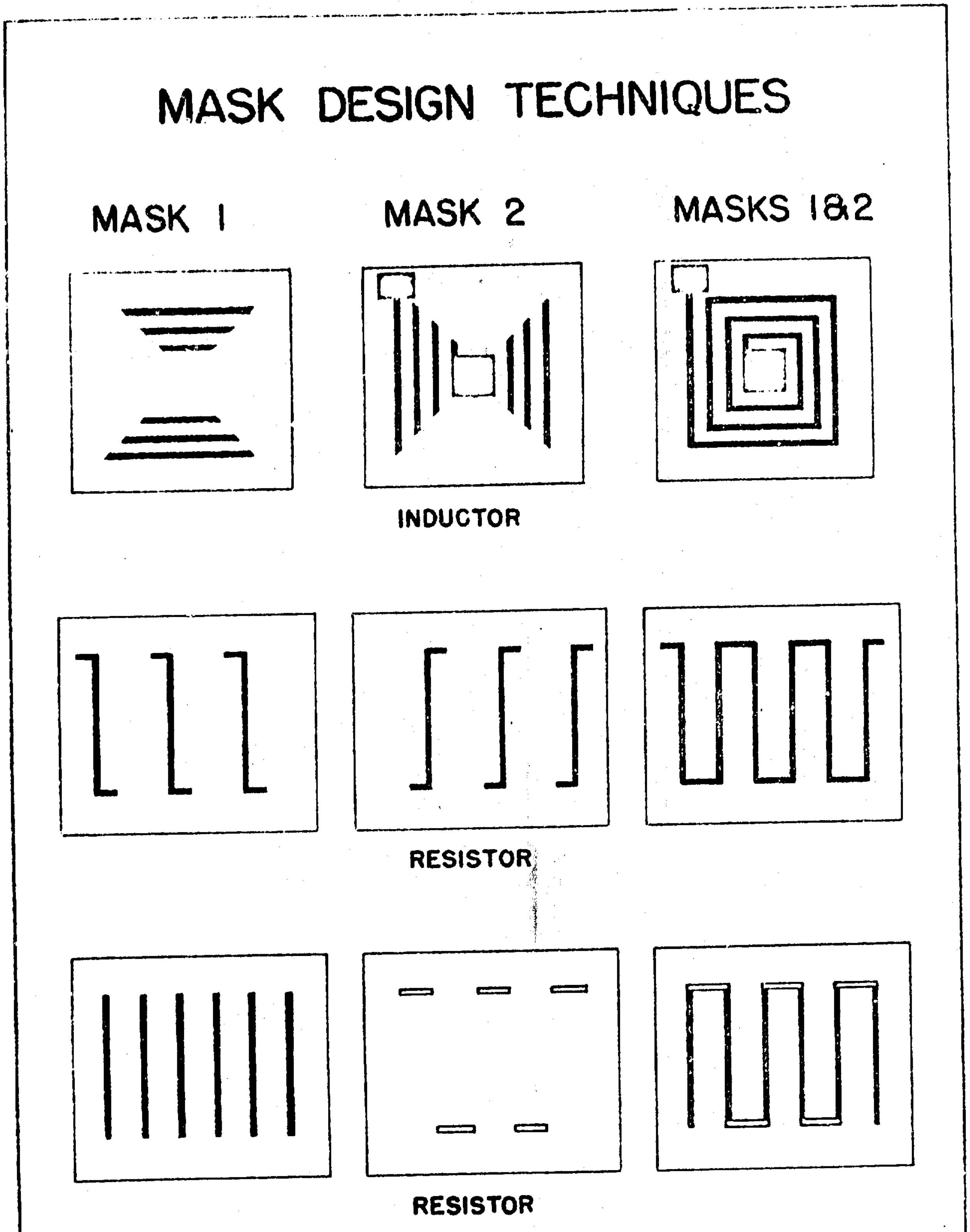

MASK DESIGN TECHNIQUES
MASK 1
MASK 2
MASKS 1&2
INDUCTOR
RESISTOR
RESISTOR

Figure 23

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To be most effective, these composite films should be deposited in a vacuum less than 5×10^{-6}mm Hg on substrates heated to at least 250°C. Wires soldered to films thusly produced cannot be pulled from the substrate without breaking the wire, disrupting the solder joint or damaging the underlying substrate.

If the leads of inserted components are to be attached to microcircuitry by thermo-compression bonding, aluminum appears to be the preferred material for conductive films. Even though aluminum films are protected by a hard adherent natural oxide coating, this oxide is readily penetrated during the thermo-compression process so that gold leads are firmly bonded.

I. ACTIVE COMPONENTS

Evaporated thin film microelectronics will probably not gain complete acceptance by industry, until active as well as passive components can be deposited. At present, neither diodes nor transistors can be deposited by techniques compatible with the deposition of other components and their interconnections. However, Dr. H. A. Stone of BTL predicts[21] "for 1970 that this problem will be overcome, and while the thin-film active devices may turn out to be very unlike transistors, they will perform some of the same functions". Until this time arrives, active components will have to be made separately and attached to the substrates by various mechanical means.

J. CONTROL OF FILM THICKNESS

Vacuum deposited films for microelectronic applications must normally be deposited to specified thicknesses. Methods of controlling film thickness may be divided into three categories, namely, optical, electrical, and mechanical.

A mechanical method that would appear satisfactory is to volatilize a weighed quantity of material. If film thickness control is critical, this method is not satisfactory because there are practical difficulties in evaporating a complete charge from a source and in preventing evaporant losses by spitting of the source material during out-gassing.

A second mechanical method of monitoring film thickness involves weighing the amount of material evaporated onto a surface of a given area. Torsion balances can be made, or purchased, that have a sensitivity of one microgram. The film to be weighed is deposited on to a balance pan placed adjacent to the substrate. The laboratories of the National Cash Register Company have found this method satisfactory for monitoring the thicknesses of evaporated magnetic films.

An electro-mechanical method of film thickness in-process control is provided by the vibrating crystal device. In this device, one face of a piezoelectric crystal is exposed to the vapor stream. The natural frequency of the crystal changes in proportion to the mass of material deposited thereon. The change in frequency is compared to a fixed frequency. Change in the difference frequency may be calibrated to indicate the amount of material deposited. Among the laboratories exploiting this method of thickness control

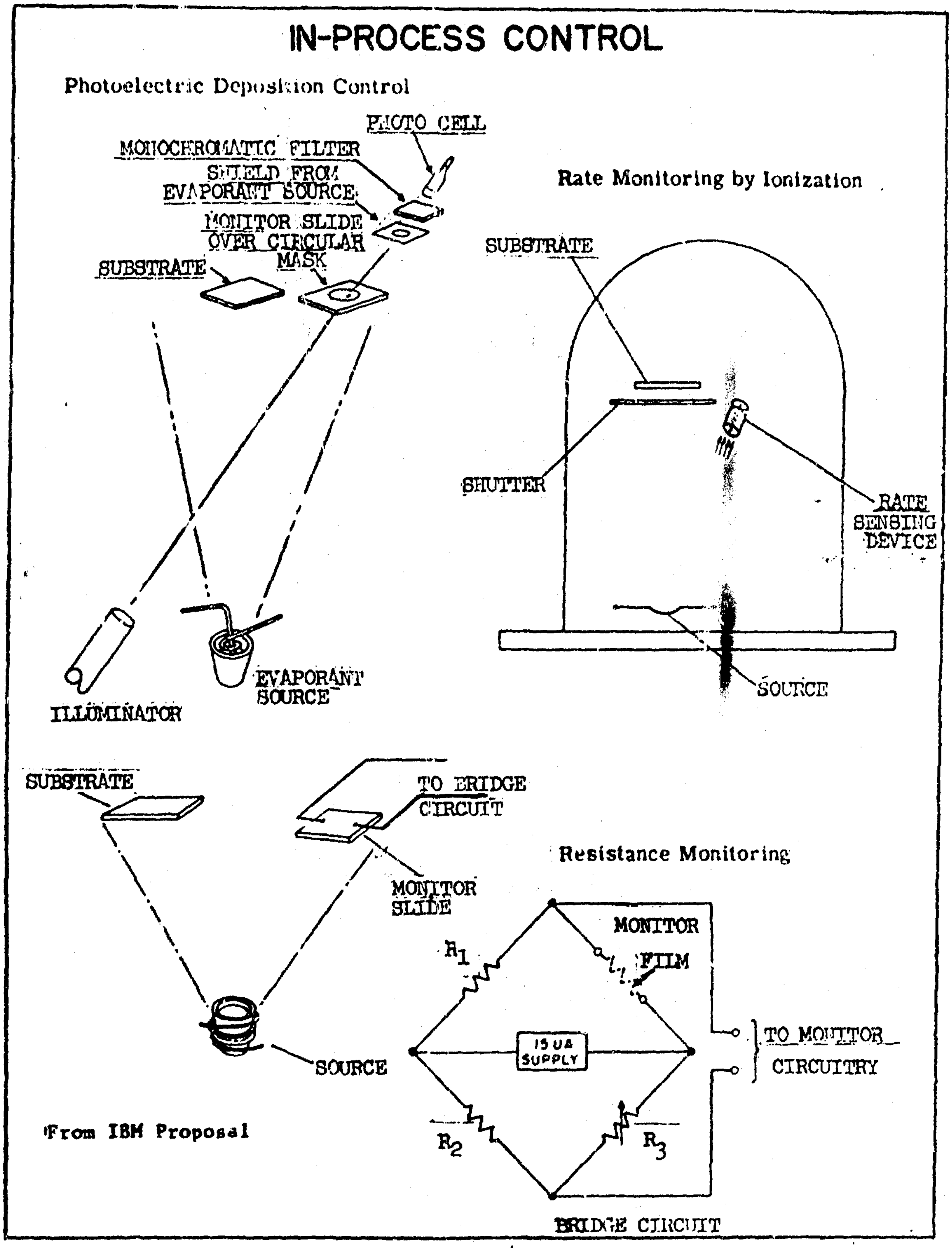
are: Varo, IBM, and Remington-Rand Univac.

Resistance determination illustrated in Figure 24 is, of course, the preferred method for monitoring resistor films. Another electrical-type in-process control illustrated in Figure 24 utilizes a modified ionization gauge as a rate sensing device, which may be used to control current to the evaporation source. IBM reports successful application of this device.

There are several optical methods for film thickness monitoring. The more common are the devices (see Figure 24) for measuring optical transmission and reflection. Another optical method is interferometry control, which is accomplished by using a photoelectric sensor to count interference peaks. It is capable of providing thickness control to 100 Angstroms.

Most monitoring devices work fairly well for batch coating, but complications arise when they are used with mask-source-substrate changers. Practically all sensing devices lose their sensitivity after more than one evaporation, and should be cleaned or compensation be made before proceeding. When used with mask-source changers, mechanical and electrical problems can be the cause of serious difficulties. Each evaporation source, theoretically, should have an associated sensing device; this means - if vacuum is maintained - that shutters or other mechanical means must be provided, to protect or move sensing devices from the outside.

Many monitoring devices have not been refined to the point where they are reliable and ready for the production line. More development work is required.



IN-PROCESS CONTROL
Photoelectric Deposition Control
PHOTO CELL
MONOCHROMATIC FILTER
SHIELD FROM EVAPORANT SOURCE
MONITOR SLIDE OVER CIRCULAR MASK
SUBSTRATE
ILLUMINATOR
EVAPORANT SOURCE
Rate Monitoring by Ionization
SUBSTRATE
SHUTTER
RATE SENSING DEVICE
SOURCE
SUBSTRATE
TO BRIDGE CIRCUIT
MONITOR SLIDE
SOURCE
Resistance Monitoring
MONITOR FILM
R_1
15 UA SUPPLY
R_2
R_3
TO MONITOR CIRCUITRY
BRIDGE CIRCUIT
From IBM Proposal

Figure 24

VI. NAFI LABORATORY PROGRESS

Paragraph 1c of BuAer (now BuWeps) Instructions for Budget Project No. 82 requested NAFI to "perform production technique work as necessary to make detailed recommendations (on microminiaturization of electronic circuits)". Accordingly, the NAFI Materials Laboratory has established an experimental plant to facilitate evaluation of the evaporated thin-film approach to microelectronics.

Selection of the evaporated thin-film approach as the subject of initial studies on microelectronics was made because:

1. The evaporated thin-film approach appeared to be nearest to realization.

2. Basic facilities were available for processing thin-film circuitry.

3. Personnel skilled in theory and technology of thin films were available.

4. Insufficient data were available on solid circuits and the "molecular" approaches to microelectronics.

5. Microcomponents (microelements) were not generally available for microcard applications.

The feasibility of fabricating thin film passive networks by high vacuum evaporation techniques was demonstrated fifteen years ago. In recent years, a few industrial laboratories - notably Varo, IBM, IRC, and CBS Electronics - have adapted these to produce laboratory samples of passive transistorized circuits on substrates one inch square, or smaller. Little data is available regarding capital equipment and production costs. This is one prime reason many concerns hesitate to use corporate funds to support such programs. Also, information is lacking on: yield, reliability, reproducibility, wattage dissipation, and environmental capabilities.

So that NAFI could be placed in a position to evaluate the thin film concept of microelectronics and to obtain a perspective view of the production problems involved, an experimental facility was established.

A. DESCRIPTION OF PHYSICAL EQUIPMENT

Equipment is available in this laboratory for evaporating two or more materials singularly, or in combination. The initial material may be in the form of chunks, wire, or powder.

In addition to placing the evaporant in boats or on filaments, two types of mechanical feed devices have been constructed. One uses vibration, and the other a screw feed. Both permit the temperature of the boats to be

pre-set. The operator has continuous manual control during the evaporation cycle. These various evaporation sources and mechanical devices permit a wide choice of evaporation programs to be set up.

Presently, this laboratory maintains four vertical vacuum coaters; one is 32", 2 are 18" and one is 24" in diameter. They have been specially designed and equipped to perform most any type of evaporation cycle. In addition, a full complement of accessories is available, such as vacuum gauges, power supplies, and monitoring equipment.

Custom-made equipment is available for making evaporation masks by some of the more advanced techniques arbitrarily classified by two systems as follows:

I. a. Disposable

b. Reusable

II. a. Negative

b. Positive

The mask making laboratory is equipped with:

arc lamp	electroplating equipment
vacuum frames	film dryer
plate whirler	dry box
vapor degreaser	photographic equipment

Supporting services consist of a drafting department, photographic laboratory, and consultants in a number of fields, such as metallurgy, chemistry, electronics, and physics. Also available for part time assistance is a well-staffed materials laboratory. This laboratory is extremely well equipped to perform a great number of qualitative and quantitative investigations. A sample of some of the major equipments at the disposal of this project are: x-ray diffraction, electron diffraction, large prism spectrograph, and infrared spectrophotometer.

B. MODIFICATION OF COATER

The NAFI Materials Laboratory is using the batch coating method for evaporating passive microcircuitry on to glass or ceramic substrates. This approach is employed because a high vacuum evaporator readily adaptable to batch coating was available. No superiority is claimed for this method over the mask-substrate-source changing procedure adopted by many investigators.

The high vacuum evaporator (Figure 29) was designed at NAFI for fabricating multi-layer dichroic optical filters. The optical properties of filters made in any one coating cycle were practically identical. This

indicated that the evaporator was capable of depositing films showing a high degree of uniformity - a desirable feature for microcircuitry fabrication.

The high degree of uniformity of coatings is assured by the compound circular motion described by the substrates during an evaporation cycle. The substrate wafers are mounted in individual holders attached to one of four circular plates counted in a horizontal plane on a revolving wheel. Thus, the substrates describe epicyclical paths during a coating cycle. The evaporation source, or sources, are located directly below the circumference of the outermost circle described by the rotating mechanisms. Theoretically, the greatest degree of uniformity of coatings is achieved when the distance from the evaporation source to the plane of the substrates is equal to the radius of the outer circle. In practice, it was found more convenient to locate the evaporation sources about twice this distance. This coice of distance was selected as a compromise between depositing films rapidly and minimizing shadowing effects of the masks at large engles.

In a coating arrangement constructed, as described above, the evaporation sources are displaced about the circumference of a relatively large circle. Each source contributes to the deposition of a uniform film on all the substrates. Hence, more than one source can be used to increase the speed of deposition, or two or more sources can be used for the co-deposition of two or more materials. Also, different types of evaporation-source heaters, such as resistance, electron bombardment and induction, can be operated simultaneously, or separately, in the evaporation chamber.

There are some undesirable physical features about this coating arrangement:

a. it has an abundance of complex moving parts

b. it lacks a convenient means of monitoring substrate temperatures.

Also, it should be noted, magnetic films cannot be evaporated onto moving substrates, because there is no convenient means for magnetically orienting moving films.

At present the NAFI coater is tooled to accommodate eleven 5/8" square substrates on each of four circular holders. Thus, 44 microcircuit patterns can be simultaneously and uniformly deposited during an evaporation cycle. An alternative arrangement provides for evaporating circuitry onto 32 substrates 1" x 1/2". (See Figures 25 and 26).

C. SiO PUMP AND SUBSTRATE HEATER

A novel arrangement w developed for simultaneously heating a substrate and providing "pumping action where it is most needed - near the heated substrate. This device, which is diagramed in Figure 27 exploits the gettering action of evaporating silicon monoxide. A description of a typical pumping cycle involving this arrangement illustrates its operation.

Current is applied to the heater coils in the SiO container, which

is in contact with the substrate, or its support, as soon as the evaporator pressure is reduced to about 10^{-2} mm Hg. The SiO temperature is maintained just below evaporation until the evaporator pressure is reduced to about 10^{-4} mm Hg. This pre-heat phase allows the SiO to outgas and the substrate to become heated. An increase in the current applied to the heater coils causes SiO to slowly evaporate and condense on the shields above the SiO container. Gettering action rapidly reduces the pressure in the evaporator to about 1×10^{-5} mm Hg. A lower ultimate pressure can be attained if the initial pressure in the evaporator is lower. Simultaneously, a substrate temperature of 200°C can be attained with the arrangement illustrated. With an improved design, wherein the SiO container will be made the heat source, much higher substrate temperatures can be expected. Substrate temperature may be adjusted by raising or lowering the SiO pump, by an arrangement operated from outside the evaporator.

Unlike other ion-getter pumps that consume the gettering material, the SiO deposited on the pump shields may be scraped off and reused. Gases, trapped during a pumping cycle, are released during the pre-heat phase of the subsequent pumping cycle. However, oxygen, which combines with the silicon monoxide, is not released, and the gettering material has to be occasionally rejuvenated by the addition of a small amount of powdered silicon.

D. MULTIPLE-BEAM INTERFEROMETER

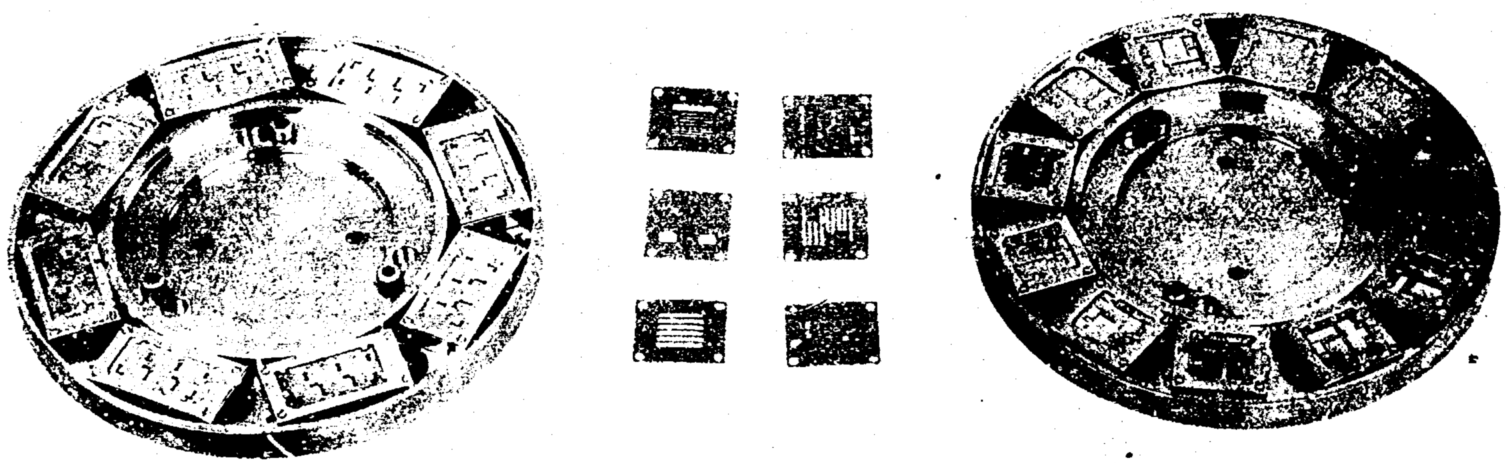
Figure 28 shows a simple multiple-beam interferometer for measuring the thickness of thin films by the Tolansky method. It measures the step height between coated and bare areas of a polished substrate wafer. Before measurements can be made, silver is evaporated onto both areas, and a flat test plate having a reflecting but semitransparent coating is placed on the silvered surface. Interference fringes - produced by multiple beam reflections of monochromatic light - are observed through a low power microscope. Film thickness is determined by comparing the offset in the interference fringes across the step, with the distance between them. The distance between fringes is a half wavelength. Under optimum measuring conditions, this method permits determination of thickness to 100 A or less.

E. PLATE WHIRLER

A special plate whirler was designed and built at NAFI to facilitate the application of photosensitive resists to glass or metal surfaces that are to be etched. Whirling speeds from 50 rpm to about 850 rpm can be attained with an interchange of two motors. A wide range of plate temperatures is also available. High whirling speeds and heating facilities are required for applying extremely thin two-layer acid resistant photosensitive layers on glass and metals that are normally difficult to etch. This whirler is versatile enough so as to be used for making circuits by the subtractive etching method such as that used in the Haloid process.

F. RESISTANCE MONITORING

A device to monitor resistance films during deposition has been assembled and placed in operation. In essence, a glass microscope slide -



SUBSTRATE HOLDERS FIG. 25

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MASK AND SUBSTRATE HOLDER

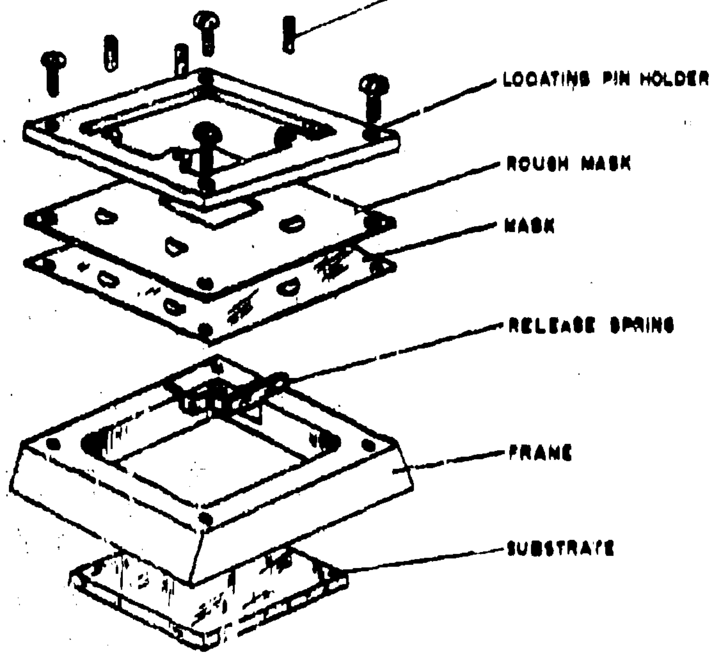

FIG. 26

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SiO PUMP AND SUBSTRATE HEATER

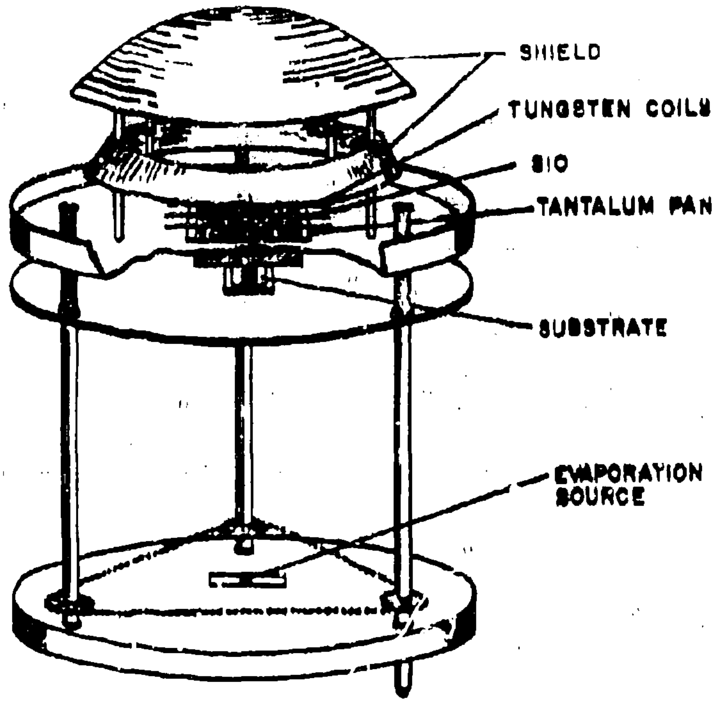

FIG. 27

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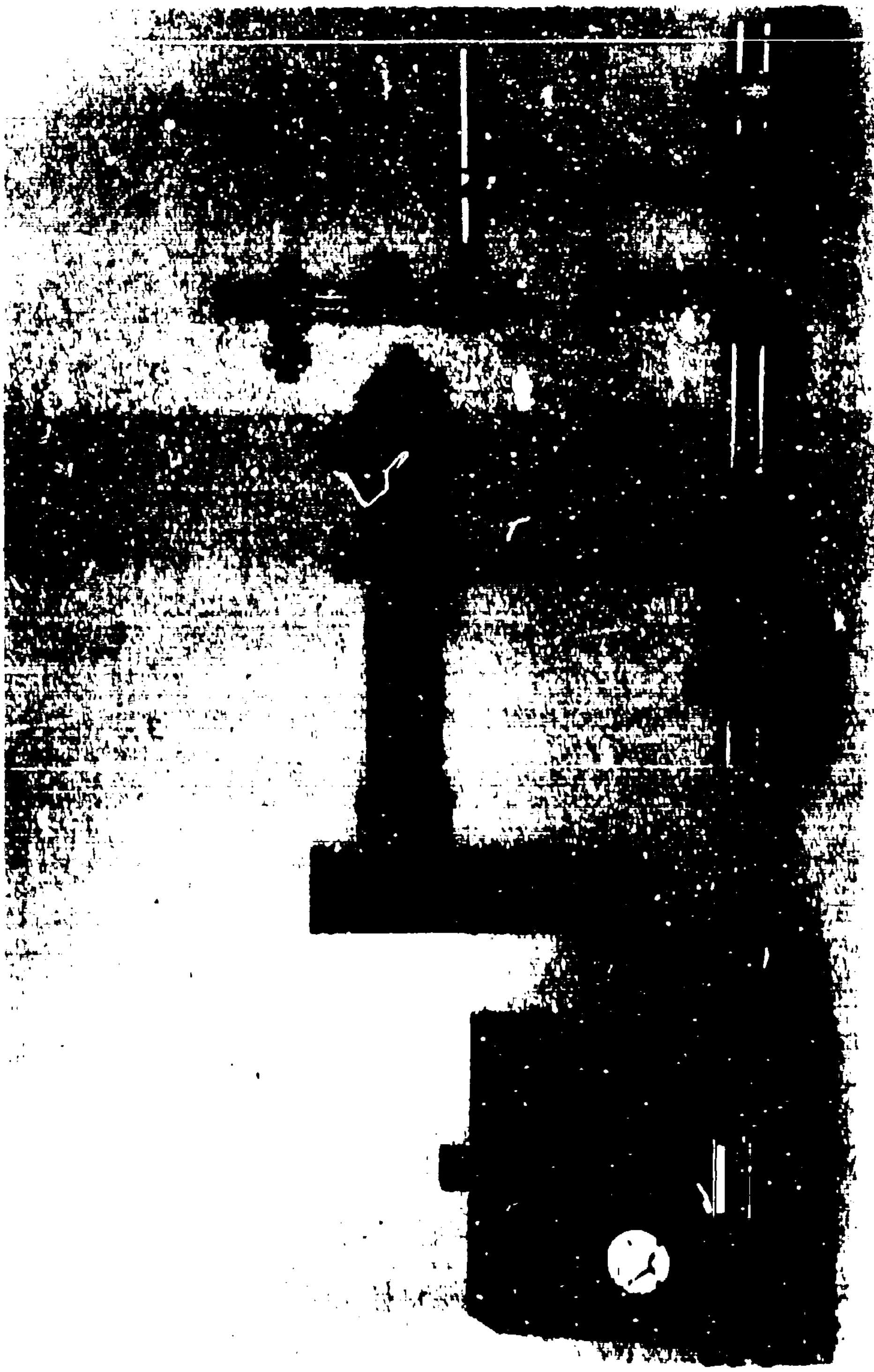


MULTIPLE BEAM INTERFEROMETER FIG. 23

with suitable leads attached - is used as one arm of a bridge circuit. The monitor slide is held in the vacuum coater in the vicinity of the substrates that are to receive the deposited film. During deposition, a digital ohmmeter indicates the resistance as the film is formed. When the proper resistance is indicated a shutter is automatically placed over the evaporation source.

G. POWER SUPPLY

For sputtering, glow discharge, and electron bombardment, a high negative voltage direct current power supply is available. It is rated at 2,500 volts and can deliver 250 milliamperes. It has an internal overload control.

H. VACUUM ARC

Some binary alloys and refractory metals are difficult to deposit in vacuum, because of their melting temperatures and vapor pressures. However, there are a few available means of attacking this problem. Other than evaporating them by electron bombardment, it is possible to use them as electrodes of a controlled arc in vacuum. Such evaporation sources may be operated on direct, pulsed direct, or alternating current, depending on the physical properties of the materials involved. Silicon-carbide may be deposited by using silicon and carbon as electrodes of an electric arc in vacuum. In order to investigate these various expediencies, a suitable controlled power supply is being built in this laboratory.

I. ATTACHING ACTIVE COMPONENTS

The present state-of-the-art does not permit the vacuum deposition of diodes, transistors, or other active circuit components. Hence, these components must be attached to the passive network. There are at least three different methods for attaching component leads to metallic conductors on glass or ceramic substrates, namely, soft soldering, ultrasonic welding, and thermo-compression bonding. If the leads are gold wires of small diameter, they can be bonded to metallized coatings by applying heat and pressure (thermo-compression bonding). A typical example: a gold wire 0.003 inch diameter can be welded by applying 180 grams force at 200°C with an inconel chisel having an edge radius approximately 2 1/2 times the diameter of the wire. While this method of welding leads to mesa transistors and other semiconductor devices is standard practice, it does not appear, at present, to be the best method of attaching components to metallized substrates. Component leads are not standardized; and in the case of PSI microtransistors, three leads having different cross sections are used. Hence, three different thermo-compression heads would be required for attaching one transistor.

Gulton Industries, Inc. has cooperated with NAFI in investigations on the ultrasonic welding method of attaching component leads to metallized surfaces. Gold-plated Dumet ribbons 0.003 inch thick by 0.018 inch wide, identical with the leads on PSI microdiodes, were ultrasonically welded to microscope slides previously coated with an evaporated chromium-gold double layer. Gulton Industries reported that a force of about 80 pounds for about 6 seconds, with their 100 watt unit, was required. The welds appeared adequate,

but were definitely weaker than soldered joints.

Ordinary soldering techniques with lead-tin solder have proved satisfactory for attaching leads to metallized glass or ceramic substrates. Adhesion is so good that soldered wires pulled parallel to the substrate cannot be removed without breaking the wire or solder, or removing some of the substrate material. Extra care must be taken if the metallic surface is gold, because gold diffuses rapidly into the solder. Gold diffusion can be reduced by using a lead-gold solder (85-15) that melts at 425°F.

Soldered joints are not as attractive as welded or bonded connections, but they are easily unsoldered and replaced, if necessary. Also, they probably can withstand as high a temperature as presently used diodes and transistors.

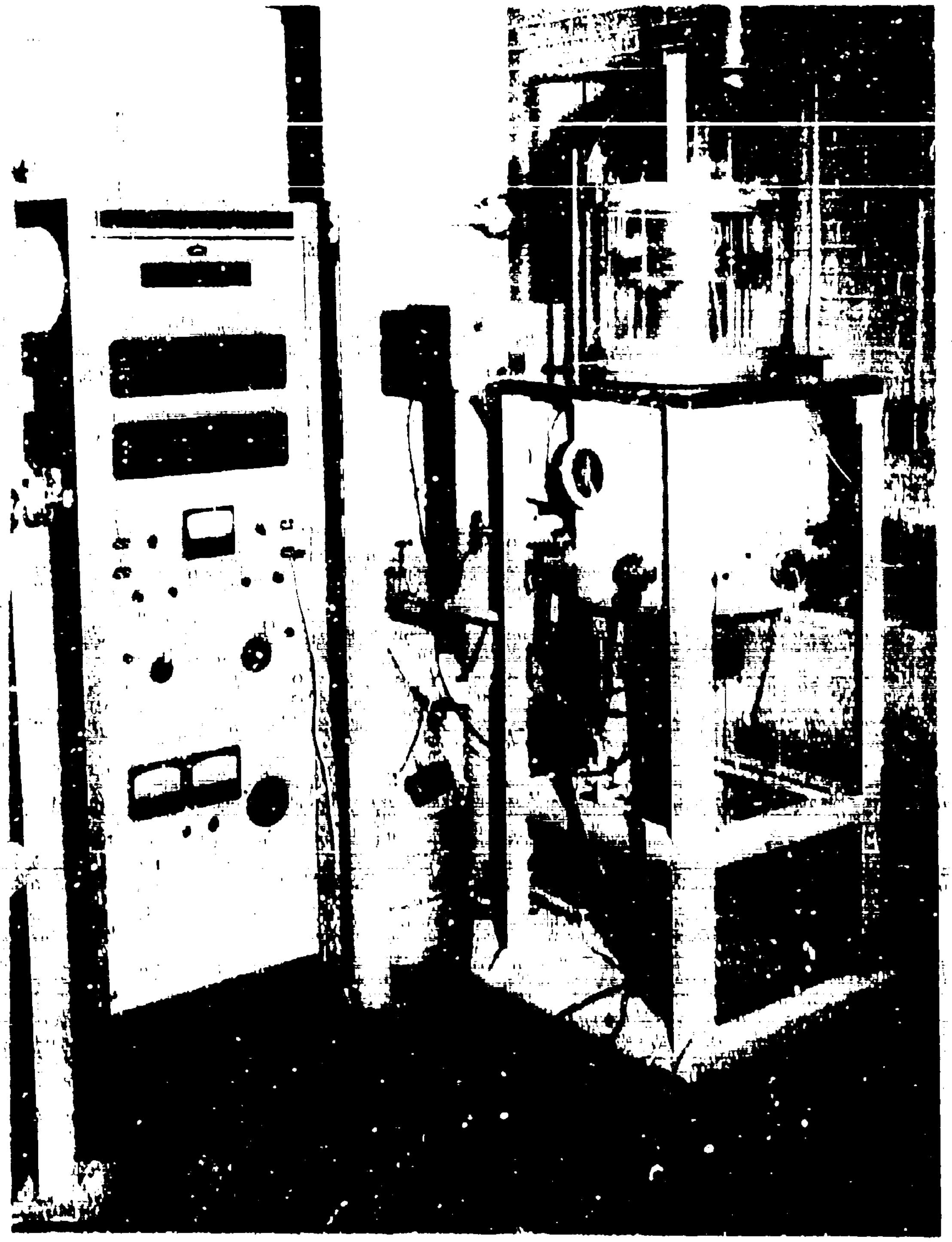
J. MASK FABRICATION

Figure 30 illustrates steps in the fabrication of improved masks by an electroforming technique using nickel. Perhaps the most important innovation is in step 6 in which a heavy layer of a metallic salt is deposited. Its masking effect in the nickel plate bath increases the fidelity of the deposited nickel stencil. Masks are plated to a thickness of from .0015" to .002".

Conventional masks, made by an etching process, cannot faithfully reproduce the art work, because of the nature of the etching process. Allowances for this must be made in the original art work. The etched pattern is always larger than the original, whereas in electroforming the reverse is true.

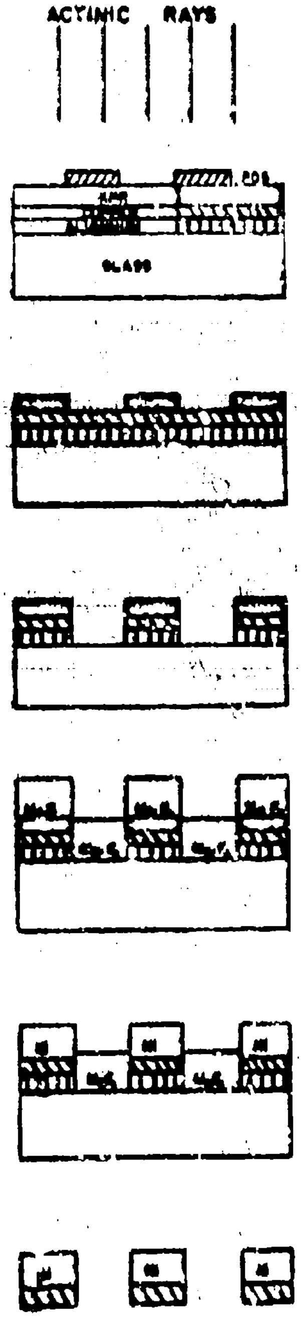
K. SCREEN PRINTING

Basic equipment for screen printing intricate patterns by both wet and dry processes are available in this laboratory. Various organic and inorganic inks can be applied to glass and ceramic substrates to form conductive and resistive patterns. Photoengraving, spray etching, and photographic equipment have been assembled for microcard processing applications. Resists and metallic paints can be screened for etching and firing, respectively.



VACUUM COATER FIG. 29

NAFI MASK FABRICATION METHOD



1. DEPOSIT COPPER-COATED ALUMINUM ON POLISHED GLASS PLATE
2. COAT WITH PHOTOSENSITIVE RESIST (KPR)
3. EXPOSE SENSITIZED PLATE THROUGH POSITIVE OF PATTERN
4. DEVELOP PLATE THUS EXPOSING METALLIC CIRCUIT PATTERN
5. ETCH AWAY EXPOSED METAL
6. VACUUM DEPOSIT THICK LAYER OF A SALT (MAGNESIUM FLUORIDE, CRYOLITE, ETC.)
7. IMMERSE PLATE IN SOLVENT TO REMOVE PHOTO RESIST. ALL OF OVERLYING SALT FILM EXCEPT THE PORTION COVERING CIRCUIT PATTERN DETAILS IS REMOVED.
8. ELECTROPLATE NICKEL ON COPPER TO THICKNESS OF APPROX. 2 MILS
9. STRIP RESULTING MASK FROM GLASS PLATE BY IMMERSING IN SOLVENT FOR ALUMINUM

Figure 30

APPENDIX A

SOURCES OF MICROMINIATURE COMPONENTS

Capacitors, ceramic

American Lava Corporation
Chattanooga, Tennessee

Mullenbach, Inc.
Los Angeles, California

Aerovox Corporation
Olean, New York

King Electronics
South Pasadena, California

Electramics Corporation
Solana Beach, California

Glenco Corporation
Metuchen, N. J.

Vitramon, Inc.
Bridgeport, Connecticut

Capacitors, tantalytic

P. R. Mallory & Company
Indianapolis, Indiana

Fansteel Metallurgical Corporation
North Chicago, Illinois

Ohmite Manufacturing Company
Skokie, Illinois

Resistors

P. R. Mallory & Company
Indianapolis, Indiana

National Research Corporation
Pearl River, N. Y.

Erie Research Corporation
Erie, Pennsylvania

Allen-Bradley Company
Milwaukee, Wisconsin

Ultronix, Inc.
San Mateo, California

Filmohm Corporation
New York, N. Y.

Mineleo Corporation
Holbrook, Massachusetts

Wilrite Products, Inc.
Cleveland, Ohio

Transistors

Pacific Semiconductors, Inc.
Culver City, California

Texas Instruments
Dallas, Texas

Transitron
Wakefield, Massachusetts

Hughes Semiconductors, Inc.
Newport Beach, California

Sylvania Electric Products, Inc.
Woburn, Massachusetts

Diodes

Pacific Semiconductors, Inc.
Culver City, California

Diodes, Inc.
Canoga Park, California

Hughes Semiconductor Division
Newport Beach, California

Transitron
Wakefield, Massachusetts

Rheem Manufacturing Company
Downey, California

Controls Company of America
Tempe, Arizona

Inductors

United States Electronics Corp.
Lyndhurst, N. J.

Electro-Winders Co., Inc.
Covina, California

Topper Mfg. Co., Inc.
Jamaica, N. Y.

Wilco Corporation
Indianapolis, Indiana

Deluxe Coils, Inc.
Wabash, Indiana

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